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Recovery Potential Assessment for Fraser River Sockeye Salmon (*Oncorhynchus nerka*) – Nine Designatable Units: Probability of Achieving Recovery Targets - Elements 12, 13, 15, 19-22

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Ten Designatable Units (DUs) of Sockeye salmon that spawn in the Fraser River watershed in British Columbia were designated as Endangered (EN) or Threatened (TH) by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2017). The eight Endangered DUs (common name and DU number in parentheses) are: Bowron-ES (Bowron DU2), Cultus – L (Cultus DU6), Takla-Trembleur-EStu (Early Stuart DU20), Harrison (U/S)-L (Weaver DU10), Seton-L (Portage DU17), Quesnel-S (Quesnel DU16), Takla-Trembleur-Stuart-S (Late Stuart DU21), and Taseko-ES (Taseko DU22). The two Threatened DUs are: Widgeon (River-Type) (Widgeon DU24) and North Barriere-ES (Upper Barriere, previously Fennell DU14). A further five DUs were assessed as Special Concern (SC): Kamloops-ES (Raft DU11), Lillooet-Harrison-L (Birkenhead DU12), and Francois-Fraser-S (Stellako DU7), Harrison (D/S)-L (Misc. Lates DU9) and Nahatlatch-ES (Nahatlatch DU13). The Recovery Potential Assessment (RPA) of the Endangered Cultus DU was covered in a separate document (DFO 2020). SC DUs were not included in the Terms of Reference for this report. However, some of the modeling results showed similar outcomes to the EN and TH DUs and have been included in this report. SC DUs are identified with an asterisk (*). This document covers RPA elements 12, 13, 15, 19-21 (i.e., quantitative analysis of recovery targets, probability of achieving recovery targets, and mitigation effects) and summarizes how these elements could contribute to element 22 (i.e., allowable harm) for the remaining 9 EN/TH DUs and the three SC DUs (i.e., Raft*, Birkenhead*, and Stellako* DU 11, 12, 7) that have a time series of stock-recruit estimates (DFO 2014). **The allowable harm assessment in this document does not include the elements covering habitat, threats, and limiting factors and should not be interpreted as being the final allowable harm statement for these DUs.**

Two nested recovery targets are proposed for the DUs, with Recovery Target #1 approximating the objective that a DU would not be characterized as Endangered or Threatened by COSEWIC or as the Red biological status of the Wild Salmon Policy (WSP) and Recovery Target #2 approximating the objective of COSEWIC for Not At Risk or WSP Green. Stock-specific stock-recruit models that account for recent productivity were used in a simulation model to evaluate the likelihood of DUs reaching the two Recovery Targets over the next three generations (12 years) over a wide range of mortality rates. A method for evaluating impacts of the Big Bar landslide on the six impacted DUs was explored, and the impacts from a range of future changes in productivity were modelled for all DUs.

1. INTRODUCTION

After the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assesses an aquatic species as Endangered (EN), Threatened (TH), Special Concern (SC), or Extirpated, Fisheries and Oceans Canada (DFO), as the responsible jurisdiction for aquatic species under the Species at Risk Act (SARA), undertakes several actions to support implementation of the Act. Many of these actions require scientific information on the current status of the species, threats to its survival and recovery, and the species' potential for recovery. Formulation of this scientific advice has typically been developed through a Recovery Potential Assessment (RPA) following the COSEWIC assessment. This timing allows for the consideration of peer-reviewed scientific assessments within SARA processes, such as when determining whether to list or not to list a species on Schedule 1 of SARA and, if listed, during the recovery planning phase that follows. A summarized rationale for COSEWIC designations of the EN/TH designatable units (DU) are as follows:

- rates of decline greater than 30% (TH) or 50% (EN) applied to:
  - Bowron, Weaver, Quesnel, Portage, Early Stuart, Late Stuart, and Taseko (DU 2, 10, 16, 17, 20, 21, 22)
- continuing decline in small populations (<2,500) applied to:
  - Bowron, Upper Barriere, Portage, and Taseko (DU 2, 14, 17, 22)
- population size less than 1,000 applied to:
  - Portage, Taseko, and Widgeon (DU 17, 22, 24)

This document covers 7 of the 22 Elements (12, 13, 15 and 19-22) as described in the RPA Terms of Reference (ToR) for 12 Designatable Units (DUs). A companion document will cover the remaining 15 Elements for these DUs and provide the final allowable harm statements. Of the 12 DUs covered in this report (Table 1), seven are designated as "Endangered" (EN), two as "Threatened" (TH), and three as "Special Concern" (SC)[1]. An additional Endangered DU, Cultus (DU6) Sockeye, was covered in a separate report (DFO 2020).

The information and analysis contained in this report represent the latest scientific information available. Changes to the environment, including but not limited to climate change, habitat degradation and human disturbance, are in flux. We cannot predict how these influences will continue to change, and therefore cannot directly predict their impact on Fraser Sockeye. Instead, a range of plausible outcomes was provided.

2. DESCRIPTION OF DESIGNATABLE UNITS

Table 1 orders Fraser Sockeye DUs by COSEWIC designation, and provides the following information: the Common Name by which a DU is often referred; which of the four Stock Management Units (SMU) a DU belongs to; the DU name (which is the same as the Conservation Unit (CU) name); DU number used by COSEWIC; whether the stock has a stock-recruit time series; and the degree of cyclic dominance the stock exhibits. In this report, stocks

[1] Special Concern DUs were not included in the Terms of Reference for this report. However, some of the modeling results showed similar outcomes to the Endangered and Threatened DUs, so they have been included. Special Concern DUs will be identified with an asterisk (*) throughout this report.

will be identified by “Common Name (DU number)”. The degree of cyclic behaviour was obtained from two sources:

1. Wild Salmon Policy (WSP) reassessment (Grant et al 2020) that identifies stocks with persistent 4-year patterns throughout the stock-recruit (SR) time series as cyclic using statistical methods; and
2. Cass and Wood (1994) which assigns stocks to three categories: consistently cyclic, inconsistently cyclic and non-cyclic using observational methods.

Table 1. Description of each DU in terms of its COSEWIC status designation, common name, stock management unit membership in 2019, its conservation/designatable unit name and number, whether long term stock-recruit data are available and whether it was considered cyclic or not.

COSEWIC Designation	Common Name	DU #	Stock Management Unit (SMU)	Designatable Unit (DU)/ Conservation Unit (CU)*	Stock-Recruit data available?**	Cyclicity	
						Wild Salmon Policy	Cass & Wood
Endangered	Bowron	2	Early Summer	Bowron-ES	Yes	Non-cyclic	Incons. cyclic
Endangered	Cultus	6	Late	Cultus-L	Yes	Non-cyclic	Incons. cyclic
Endangered	Early Stuart	20	Early Stuart	Takla-Trembleur-EStu	Yes	Cyclic	Consist. cyclic
Endangered	Weaver	10	Late	Harrison (U/S**)-L	Yes	Non-cyclic	Non-cyclic
Endangered	Portage	17	Late	Seton-L	Yes	Non-cyclic	Consist. cyclic
Endangered	Quesnel	16	Summer	Quesnel-S	Yes	Cyclic	Consist. cyclic
Endangered	Late Stuart	21	Summer	Takla-Trembleur-Stuart-S	Yes	Cyclic	Consist. cyclic
Endangered	Taseko	22	Early Summer	Taseko-ES	No	Non-cyclic	-
Threatened	Upper Barriere (Fennell)	14	Early Summer	North Barriere-ES	Partial*	Non-cyclic	-
Threatened	Widgeon	24	Summer	Widgeon (River-Type)	No	Non-cyclic	-
Special Concern	Nahatlatch	13	Early Summer	Nahatlatch-ES	No	Non-cyclic	-
Special Concern	Raft	11	Summer	Kamloops-ES	Partial*	Non-cyclic	Incons. cyclic

COSEWIC Designation	Common Name	DU #	Stock Management Unit (SMU)	Designatable Unit (DU)/ Conservation Unit (CU)*	Stock-Recruit data available?**	Cyclicity	
						Wild Salmon Policy	Cass & Wood
Special Concern	Birkenhead	12	Late	Lillooet-Harrison-L	Yes	Non-cyclic	Non-cyclic
Special Concern	Stellako	7	Summer	Francois-Fraser-S	Yes	Non-cyclic	Incons. cyclic
Special Concern	Misc. Lates	9	Late	Harrison (D/S)-L	No	Non-cyclic	
Not At Risk	Scotch & Seymour	19	Early Summer	Shuswap-ES	Partial	Cyclic	Consist. cyclic (Seymour)
Not At Risk	Nadina	8	Early Summer	Nadina-Francois-ES	Yes	Non-cyclic	Incons. cyclic
Not At Risk	Chilliwack	5	Early Summer	Chilliwack-ES	No	Non-cyclic	
Not At Risk	Gates	1	Early Summer	Anderson-Seton-ES	Yes	Non-cyclic	Consist. cyclic
Not At Risk	Late Shuswap	18	Late	Shuswap Complex-L	Yes	Cyclic	Consist. cyclic
Not At Risk	Pitt	15	Early Summer	Pitt-ES	Yes	Non-cyclic	Non-cyclic
Not At Risk	Harrison	23	Summer	Harrison (River-Type)	Yes	Non-cyclic	
Not At Risk	Chilko	4	Summer	Chilko-S	Y	Non-cyclic	Incons. cyclic
Not Assessed	Chilko	3	Summer	Chilko-ES***	N	Non-cyclic	

* CU and DU naming conventions include the following abbreviations:

- ES – Early Summer SMU
- EStu – Early Stuart SMU
- S – Summer SMU
- L – Late SMU
- U/S = Upstream
- D/S = Downstream

** DUs labelled “partial” in the Stock-Recruit Data Available column have components which do not have a full stock-recruit time series within the DU. Only the portion of the DU with a stock-recruit time series was modelled.

***the Chilko-ES DU was not assessed separately from the Chilko-S DU and is generally included as part of the Chilko stock and Summer Run SMU.

3. BACKGROUND & OVERVIEW

For fishery management purposes Fraser River Sockeye salmon are grouped into four Stock Management Units (SMUs) based on marine timing: Early Stuart (EStu), Early Summer (ES), Summer (S) and Late (L) (Table 2). Harvest control rules (HCRs) are applied at the SMU level. The migrations of these SMUs are not discrete, so there is substantial overlap except during the earliest and latest portions of the overall Sockeye migration. Thus, management actions taken to affect one SMU will often affect adjacent SMUs. Individual DUs within each SMU similarly demonstrate different spatial and temporal patterns in their return migrations that partially overlap with each other and with DUs in other SMUs.

The current escapement planning regime or one similar to it has been in place since 2006. Aspects of the regime include abundance-based HCRs called Total Allowable Mortality rules (TAM rules) that are applied annually at the SMU level. TAM rules are cycle-line and SMU-specific HCRs that define the escapement goal.

In order to achieve escapement goals, the difference between estimates (DBEs) of the number of Sockeye that migrate past Mission, BC in the lower Fraser River and the number of Sockeye that arrive on the spawning grounds (excluding catch) needs to be taken into account. Models are used in-season to project the DBEs. Fraser River water temperatures and discharge levels are the primary drivers for Early Stuart, Early Summer and Summer run DBE projections while in-river migration timing drives Late run DBE projections. The allowable mortality from the TAM rule minus projected DBE generates the ER for the SMU. A minimum ER of 10-20% is applied when the calculated ERs are less than the minimum ERs to allow for harvest of more abundant co-migrating stocks or species.

Pre-season, annual adjustments to TAM rules can be made to account for co-migrating stocks of concern and for other year-specific circumstances. Annual HCRs are subject to a pre-season consultation process with First Nations and other stakeholders as captured in each year's Salmon Integrated Fisheries Management Plan for Southern BC (IFMP) published by DFO. In-season, the allowable ERs change with stock abundance and estimates of projected DBEs.

The pre-season exploitation rates (ER) established in the IFMP for each SMU are abundance-based and tend to be driven by the DUs with the largest abundance. In addition, most measures to protect a particular DU would affect other DUs due to overlapping migration timing and patterns. It is often the more abundant Not At Risk DUs, such as Chilko in the Summer SMU, that is most abundant and therefore greatly influences the allowable ER for the SMU. Table 2 shows the DUs grouped by COSEWIC designation within each SMU.

Table 2. COSEWIC designation of the component stocks within each SMU.

Status	Early Stuart	Early Summer	Summer	Late
Endangered	Early Stuart (DU20)	Bowron (DU2) Taseko (DU22)	Late Stuart (DU21) Quesnel (DU16)	Cultus (DU6) Weaver (DU10) Portage (DU17)
Threatened	-	Upper Barriere (DU14)	Widgeon (DU24)	-
Special Concern	-	Nahatlatch* (DU13)	Stellako* (DU7) Raft* (DU11)	Birkenhead* (DU12) Misc. Lates* (DU9)
Not At Risk	-	Scotch & Seymour (DU19) Nadina (DU8) Gates (DU1) Pitt (DU15) Chilliwack (DU5)	Chilko (DU4) Harrison (DU23)	Late Shuswap (DU18)
Not Assessed	-	Chilko Early Summer (DU3)	-	-

Pre-season assessments of how implementation of the HCR will impact small stocks and stocks of concern are performed in two ways. First, in the IFMP as arithmetic calculations based on a range of pre-season abundance forecasts and median DBEs and, second, by use of a detailed fisheries planning model by the bilateral (Canada and the United States) Fraser River Panel (FRP).

Pre-spawn mortality (PSM) was not explicitly included in these assessments because escapement goals use total spawners as the unit of measure as opposed to effective spawners. PSM was implicitly included in the SR models used to assess HCR performance, by way of the parameter values utilized.

In-season, fisheries that target Fraser River Sockeye are actively managed by a process involving the FRP, its Technical Committee and Pacific Salmon Commission (PSC) staff. Daily test fisheries that provide abundance and migration-route information as well as physical samples (DNA and scales) for stock identification purposes are conducted by the PSC, US and Canada. These operate in marine areas (e.g., Johnstone Strait, Juan de Fuca Straight, Straight of Georgia, San Juan Islands) and in the Fraser River (e.g., Cottonwood, Whonnock, Qualark). Commercial fishery catches are similarly sampled. The data are augmented by hydroacoustic programs conducted near Mission and farther upstream at Qualark that provide daily estimates of migrating fish abundance. Visual confirmation of fish passage and fish condition is accomplished through an observer at Hells Gate, which is a known point of difficult fish passage. The data collected through these programs are analyzed by PSC staff to provide the FRP with a minimum of twice-weekly updates of run size, migration route, DBE, spawning escapement target and harvest-to-date by SMU and smaller groupings of stocks. The FRP considers this information and uses it to adjust fishery plans to achieve goals for spawning escapement and harvest.

Finally, post-season assessments of the data and programs feed back into the system, which results in improved data quality in the historical databases used for various models including those used for forecasts and in-season assessments.

4. METHODS

4.1. DATA SOURCES

Data sources for this assessment include estimates of spawners, recruits, and differences between estimates (DBE). The stock-recruit (SR) time series contains spawner and recruit data beginning as early as brood year (BY) 1948 (but as late as 1981), with most ending in BY2013. The first year of the SR time series lines up with those used for Wild Salmon Policy status assessments (Grant et al 2020). For most Fraser Sockeye, which spawn as 4 and 5-year-olds, return years that correspond to BY2013 are 2017 and 2018, respectively. Harrison Sockeye spawn predominantly as age 3 and 4-year-olds, so their recruitment data are complete up to BY2014. Historical spawner data were obtained from DFO's Fraser Interior Area Stock Assessment, while adult returns were provided by PSC staff.

DBEs refer to differences between estimates of adult Sockeye passage at Mission, BC (measured by the PSC in a hydroacoustic and test fishery program) and adult Sockeye on the spawning grounds, after accounting for the catch that occurs in between. DBEs for 2002-2016 were provided by the PSC. The data were limited to this time period because the stock resolution required for this analysis was available only for years when DNA methods were used for stock identification.

Exploitation rates for Taseko (DU22, Figure 41) and Widgeon (DU24, Figure 20) were taken from proxies. ERs in years up to 2011 came from the COSEWIC assessment (COSEWIC 2017) for similarly timed stocks – Bowron (DU2) in the case of Taseko, and Harrison (DU23) for Widgeon. Exploitation rates for 2012-2018 were taken from SMU ERs sourced from post-season reports and presentations by the PSC – Early Summer for Taseko and Summer for Widgeon.

4.2. METHODS OVERVIEW

A description of methods used in this paper can be found in the following sections:

Stock-recruitment model selection (5.3.1 - 5.3.3)

Forward simulations – current productivity (5.4.2)

Forward simulations – alternative productivities (6.1.2)

Forward simulations – Big Bar landslide mitigation (6.1.3)

For the remainder of the paper, the focus is on the DUs that were designated as Endangered, Threatened, or Special Concern.

5. RECOVERY TARGETS

5.1. CONTEXT: ALLOWABLE HARM & RECOVERY TARGETS

5.1.1. Allowable harm

While human-induced mortality was expressed as an "exploitation rate" in this analysis, it is important to note firstly, that ER was modelled because it is the easiest management lever to change quickly, and secondly, the ERs modelled should not be explicitly interpreted as an allowable fisheries ERs on adult salmon. Other factors that were implicitly bundled with, but not explicitly modelled by the "exploitation rate" include: in-river mortality above modelled rates; mortality associated with fishing activities directed at Sockeye or other species, including direct and indirect physical and physiological injury (i.e., through release, depredation or gear avoidance); natural predation; and habitat impacts on migratory adults. Thus, ER in the scenarios should be interpreted as a combination of direct mortalities from anthropogenic sources (e.g., fishing); indirect mortalities from anthropogenic sources (e.g., en-route mortality exacerbated by climate change); and natural mortalities above the historical levels modelled (e.g., predation). All factors contributing to mortalities should therefore be considered in addition to ER and productivity when considering allowable harm and overall recovery potential. Note that historical levels of in-river mortality was included in the models for all DUs, in addition to the scenarios associated with the Big Bar landslide for DUs that spawn upstream of the blockage.

While the model incorporates uncertainty in our understanding of stock-recruit dynamics and a wide range of natural variability in the population projections, it does not include any outcome uncertainty (i.e., implementation error) on the exploitation rate.

5.1.2. Recovery Targets

The identification of status by both COSEWIC and WSP involves gathering and synthesizing advice from experts over multiple days. The criteria and modeling methods used here are a simplified mixture of these processes and do not capture the nuances in these approaches.

In addition, the algorithm used in this analysis was applied to model projections to represent probabilistic status outcomes in the future as opposed assessing the current population status, which was the focus of both COSEWIC and WSP.

5.2. ELEMENT 12: PROPOSE CANDIDATE ABUNDANCE AND DISTRIBUTION TARGET(S) FOR RECOVERY

Recovery Targets are based on biological information about the stock and exclude social, economic, cultural and ecosystem considerations. To help track a stock's progression towards recovery, two Recovery Targets were identified:

- Recovery Target #1: approximates the objective that a DU not be characterized as Endangered or Threatened by COSEWIC or as the Red biological status of the Wild Salmon Policy (WSP).
- Recovery Target #2: approximates the objective of COSEWIC for Not At Risk or WSP Green.

Although there was a low probability that a DU categorized as EN/TH could reach Recovery Target #2 in three generations, we proposed this target as a longer term aspirational target that more fully meets the intended definition of a "recovered" DU. Recovery Target #1 was proposed as an intermediate target against which progress can be more easily measured in the short term. To calculate the probability of each DU reaching each Recovery Target, the criteria described in this section were applied to model projections (5.3 and 5.4).

5.2.1. Conceptual Recovery Targets

Recovery Target #1 represents the minimum requirements for not designating a DU as Endangered or Threatened. As COSEWIC criteria use performance measures and benchmarks that are independent of the DU being assessed, a stock-specific WSP lower abundance benchmark (S_{gen}) was added to prevent cases where a severely negative rare event, such as the Big Bar landslide that blocked portions of the 2019 migration, reduced the first generation of spawners so much that subsequent simulated generations showed improvement simply due to the very low abundance it was compared to. S_{gen} is the “spawner abundance that will result in recovery to S_{MSY} in one generation in the absence of fishing under equilibrium conditions” (Holt et al. 2009). S_{gen} values were adapted from the values provided in Grant et al. (2020) as described in section 5.2.2 and shown in Table 4. To construct the algorithm for defining Recovery Target #1, criteria used by COSEWIC to determine stock designations (Table 3) were combined with stock-specific benchmarks used for WSP status assessments (Table 4) to create a check list (Table 5).

Recovery Target #2 represents a COSEWIC “Not At Risk” designation or a WSP “Green” biological status. The criteria for achieving COSEWIC’s “Not At Risk” designation are varied and the distinction between “Special Concern” and “Not At Risk” employs a number of qualitative criteria (COSEWIC 2018), therefore Recovery Target #2 relies on WSP methods (Holt et al. 2009) and stock-specific benchmarks (Table 4).

Table 3. Summary of select criteria used by COSEWIC to determine DU designations, and the corresponding performance measures that need to be met in order to not trigger the COSEWIC criteria.

Stock	COSEWIC Criteria *	Performance Measures
Bowron (DU2)	A2b and C2a(ii)	mature individuals > 10,000 AND rate of decline <=30% OR mature individuals < 10,000 AND rate of change is positive
Weaver (DU10)	A2b	rate of decline <= 30%
Upper Barriere (DU14)	C2a(ii)	mature individuals < 10,000 AND rate of change is positive
Quesnel (DU16)	A2b	rate of decline <= 30%
Portage (DU17)	A2b and C2a(ii) and D1	mature individuals > 1,000 (to get out of D1) AND mature individuals > 10,000 AND rate of decline <=30% OR mature individuals < 10,000 AND rate of change is positive
Early Stuart (DU20)	A2b and A4b	rate of decline <= 30%
Late Stuart (DU21)	A2b and A4b	rate of decline <= 30%
Taseko (DU22)	A2b and C2a(ii) and D1	stock not modelled
Widgeon (DU24)	D1	stock not modelled

*A2b and A4b both refer to rate of decline greater than 30% (TH) or 50% (EN)
C2a(ii) continuing decline in small (<1,000) populations
D1: population less than 1,000

5.2.2. Stock-specific Recovery Target benchmarks

Stock-specific Recovery Target abundance benchmarks were adapted from Grant et al. (2020), which used methodologies from Holt et al. (2009). For DUs with multiple values for the same benchmark, all of the potential median values presented in Grant et al. (2020) were averaged and rounded to the nearest 100 fish. The adapted lower (S_{gen}) and upper WSP biological benchmark values are shown in Table 4. Updated values for these benchmarks were not calculated as part of this analysis.

Note that Grant et al. (2020) calculated benchmarks using effective adult spawners, but this analysis used total adult spawners, which includes both successful spawners and pre-spawn mortalities. Use of WSP abundance benchmarks therefore results in a slightly optimistic skew towards achieving WSP "Green" status, since the numbers of total adult spawners reaching the spawning grounds were compared to a benchmark where the units are adult spawners that have both reached the spawning grounds and successfully spawned. None of the EN/TH stocks reached Recovery Target #2 in the three generation time frame being modelled, so this factor did not affect the preliminary Allowable Harm conclusions in section 8.

Table 4. Lower (S_{gen}) and upper WSP biological abundance benchmark values adapted from Grant et al. (2020). These values were used as criteria to assess the achievement of Recovery Targets (see Table 5).

Common Name (DU name)	**Lower WSP Biological Benchmark (S_{gen})**	**Upper WSP Biological Benchmark**
Early Stuart, DU 20 (Takla-Trembleur-EStu)	107,900	350,100
Bowron, DU 2 (Bowron-ES)	5,100	19,000
Upper Barriere, DU 14 (North Barriere-ES)	600	5,100
Quesnel, DU 16 (Quesnel-S)	192,300	1,302,800
Late Stuart, DU 21 (Takla-Trembleur-Stuart-S)	126,400	590,400
Raft*, DU 11 (Kamloops-ES)	5,000	17,800
Stellako*, DU 7 (Francois-Fraser-S)	24,300	122,600
Portage, DU 17 (Seton-L)	2,200	13,500
Weaver, DU 10 (Harrison (U/S)-L)	10,700	84,600
Birkenhead*, DU 12 (Lillooet-Harrison-L)	14,900	79,000

5.2.3. Nested recovery targets - methodology

Based on the performance measures outlined in 5.2.1 and 5.2.2, a series of tests were devised to determine whether a DU reached the Recovery Targets. Table 5 shows two different pathways, or combinations of criteria, by which a DU could meet each Recovery Target. Which pathway to use was determined by DU abundance. In Path A, DUs that had between 1,000 – 10,000 mature individuals in the last generation must also have an increasing three generation slope to reach Recovery Target #1. In Path B, DUs that had abundances larger than 10,000 mature individuals needed a three generation decline no greater than 30%. DUs with fewer mature individuals in the last generation than 1,000 or the stock-specific WSP S_{gen} benchmark (Table 4) did not meet either Recovery Target. Due to the nested nature of the Recovery Targets, a DU that met Recovery Target #2 also met Recovery Target #1. To reach Recovery Target #2 under either Path A or B, the DU needed to have an average number of mature individuals in the last generation that was greater than the upper WSP abundance benchmark in Table 4.

Table 5. Criteria used to determine whether projections for a given DU reached Recovery Target #1 and/or #2. Each Recovery Target can be met by two different combinations of criteria (Path A or Path B). Note that Recovery Target #2 uses the same two criteria pathways as Recovery Target #1, but adds one additional criterion. Criteria were designed to approximate, but not exactly match COSEWIC and WSP expert-driven status categorization approaches.

	Recovery Target #1		**Recovery Target #2**	
Criteria Questions	*Path A*	*Path B*	*Path A*	*Path B*
Is the average number of mature individuals in the last generation larger than the S_{gen} value (Table 4)?	Yes	Yes	Yes	Yes
Is the average number of mature individuals in the last generation greater than 1k?	Yes	-	Yes	-
Is the 3 generation slope increasing?	Yes	-	Yes	-
Is the average number of mature individuals in the last generation greater than 10k?	-	Yes	-	Yes
Is the 3 generation slope doing better than a 30% decline?	-	Yes	-	Yes
Is the average number of mature individuals in the last generation larger than the upper WSP abundance benchmark (Table 4)?	-	-	Yes	Yes

5.3. ELEMENT 13 (PART 1): PROJECT EXPECTED POPULATION TRAJECTORIES OVER A SCIENTIFICALLY REASONABLE TIME FRAME (MINIMUM OF 10 YEARS), AND TRAJECTORIES OVER TIME TO THE POTENTIAL RECOVERY TARGET(S), GIVEN CURRENT [WILDLIFE SPECIES] POPULATION DYNAMICS PARAMETERS – STOCK SPECIFIC SR MODELS

Previous RPAs for Pacific salmon have used a wide variety of time frames for assessing recovery potential, ranging from 3 generations (Interior Fraser Coho) to 40+ years (Okanagan Chinook, Thompson/Chilcotin Steelhead). This RPA for Fraser River Sockeye focuses on near-term trajectories (3 generations, 12 years) for reasons described in section 7.1.2. Namely, a long time frame would not be useful for this analysis because long term (12 generation) results were more a function of SR model choice than starting conditions (Huang 2014).

Of particular concern for the RPA, the combination of models parameterized using long term historical productivity (e.g., Bayesian Ricker and Bayesian Larkin stock-recruit models) and seeded with recent spawner abundances that were very low relative to the long-term averages resulted in strong overcompensation effects. This resulted in modelled population abundances that could be viewed as having "Recovered" in two or three generations. This was not supported by real life observations. For example, declines in Early Stuart Sockeye abundance since the mid 1990s has not resulted in increased productivity or overall returns despite a substantial reduction in exploitation rate (from 60% to 15%) during the same time period.

Because of this disconnect between long-term averages and what has been observed in recent years, two one-day workshops with a small group of stock-recruit model experts were held to determine how to choose stock-specific SR models for this analysis (see sections 5.3.1 and 11).

This section describes the stock-recruitment model forms used in this analysis and provides an overview of model selection methods. Further details on model selection methods are in Appendix 1 (11.2-11.4).

5.3.1. Methods: stock-recruit model selection

The choice among alternative models is typically based on a comparison between predicted values and observed values (i.e. residuals), summarized using performance measures (e.g., Mean Absolute Error, MAE).

There are two basic approaches for generating residual-based performance measures:

- The typical test for statistical model evaluation uses all the data to fit the model and calculate expected values, which are then compared to observed values.
- *Retrospective* tests are commonly used to test the performance of alternative forecast models (e.g., Grant et al. 2020, Vélez-Espino et al. 2019). In those tests, data up to year y are used to fit the model and generate a forecast for year y+1, and that forecast is compared to the observed value for year y+1. The data up to year y+1 are then used to fit the model and generate a forecast for year y+2, and so on.

In this analysis, a modified process combining aspect of both approaches to test the candidate SR models was used (section 5.3.2, Appendix 1):

- SR parameters were estimated once using all years of data and then applied to all brood years, instead of being re-estimated in each year.
- Individual performance measures and aggregate ranks were calculated for two generation (i.e., eight year) time windows, rather than for the entire available data set. The pattern in

ranks over time as well as ranks for the most recent brood years (2011-2013, i.e., included recruits up to and including 5 year olds from 2018) were considered.

The intent of this approach was to address the question: *How closely do the recruit estimates generated by this SR model come to the observed recruitments in different time periods?*

Performance measures consistent with the forecast methods used for Fraser Sockeye (Grant et al. 2020) and BC Chinook salmon (Vélez-Espino et al. 2019) were identified and the scaled ranking approach described in Folkes et al. (2018) was applied. The performance measures were Mean Raw Error (MRE), Mean Absolute Error (MAE), Mean Percent Error (MPE), Mean Absolute Percent Error (MAPE) and Root Mean Square Error (RMSE). Each performance measure captures a different aspect of model performance (e.g., accuracy versus bias).

The intent of scaled ranking is to capture not only the sequence of values, but also how close they were. For example, the values [5, 5.2, 18, 26] have ordinal ranks [1,2,3,4], but the first two are actually very close, and the other two are more distant. Scaled ranking considers the distance between the smallest and largest value and adjusts the ranks for intermediate values accordingly, producing ranks of [1, 1.03, 2.85, 4] in this example.

To rank the SR models for each stock, the scaled ranks were calculated separately for each SR model and for each performance measure, then averaged the ranks across performance measures with equal weighting applied.

Appendix 4 (14.3) documents the R functions used to implement the ranking scheme.

5.3.2. Methods: basic model forms

Many alternative SR model forms were evaluated (11.1 in Appendix 1), but only the short-listed candidate models for the RPA are described here.

Ricker – long term productivity – Bayesian Ricker (RA)

The Ricker model is commonly used to represent stock-recruit dynamics of Pacific salmon. The basic Ricker and Larkin stock-recruit models were the basis for the model variants that were used for forward simulations.

$$\ln (R_t/S_{t-4}) = \alpha - \beta_0 S_{t-4} + \varepsilon_t$$

Where *R* is the recruits in year *t, S* is the spawners from the brood year *t, α* is the productivity parameter, α/β_0 describes the capacity of the system for the Ricker equation and ε is the process error in recruitment.

Larkin – long term productivity – Bayesian Larkin (LA)

The Larkin model adds delayed density dependence to the Ricker model in the form of three “lag beta” terms and approximates the cyclic pattern observed in some Fraser Sockeye stocks:

$$\ln (R_t/S_{t-4}) = \alpha - \beta_0 S_{t-4} - \beta_1 S_{t-5} - \beta_2 S_{t-6} - \beta_3 S_{t-7} + \varepsilon_t$$

Ricker – recent productivity – recursive Bayesian Ricker (RRB)

A Bayesian formulation of the Kalman filter model in Peterman et al. (2003) was obtained from Catherine Michielsens (Pacific Salmon Commission). The RRB model includes a time-varying alpha parameter which acts as a proxy for historical patterns of productivity. The parameter estimates generated from the RRB model were: an α estimate for each brood year, and an estimate of β and ε for the stock.

The observation error and process error in the original Bayesian code was combined into a single term for the purpose of simplifying the model and because we anticipated changing it further to work with the recursive Bayesian Larkin stock-recruit model (LRB).

An informative prior for alpha was taken from the stock-specific alpha (median and standard deviation) estimated by the non-recursive Bayesian Ricker model (RA). The beta prior was obtained as described in Pestal et al. (2012), that is, using a lognormal distribution with a mean of the largest observed abundance and an upper bound of three times the largest observed value.

To represent the current productivity of each stock, 10,000 MCMC sample sets each containing an alpha, beta and a variance term were sampled from the posterior distribution from each of the last four years estimated by the RRB model . For the base case forward simulations (section 5.4.2), these 40,000 sample sets were sub-sampled (1,250 samples from each of the last four years for a total of 5,000 samples) to represent average productivity in recent years. Each forward simulation used one of the 5,000 MCMC samples taken from the last 4 years of parameter estimates. The 40,000 MCMC sample sets will resurface later in section 6.1.2 for the discussion of alternative future productivities.

Larkin - recent productivity – recursive Bayesian Larkin (LRB)

These models used the same method as the RRB model, except using the Larkin stock-recruit model form. The three lag beta terms had uniform priors bounded by 0 and 100, as was used in Pestal et al. (2012). The alpha prior was taken from the non-recursive Larkin model (LA). MCMC sample processing as described for the RRB model.

Ricker – recent productivity – Bayesian 5 generation (R5Gen)

These model runs used the same method as the RA model, but the time series of SR numbers used to estimate the parameters was restricted to the last 20 brood years, which is equivalent to five generations of age 4 Sockeye. 5,000 MCMC samples were taken for use in the base case forward simulation models (section 5.4.2) and 10,000 MCMC samples were set aside for use in the alternative future productivity scenarios (section 6.1.2).

5.3.3. Methods: stock-recruit model selection criteria

This section relates to the Figure A flow diagram. Using the results (i.e., simulated residuals) generated in section 5.3.1, the following steps were used to select stock-specific stock-recruit models. Our objective was to select models that reflected the recent lower-than-average productivity demonstrated by the Endangered and Threatened stocks (see 11.2 in Appendix 1). The models that most reliably picked up on the recent low productivity were the three recent productivity models: recursive Bayesian Ricker (RRB), recursive Bayesian Larkin (LRB) and the Bayesian 5 Generation Ricker (R5Gen). (Step 1, Figure A)

First preference was given to the recursive model forms (LRB & RRB) as all years of stock-recruit information were used. In the preliminary rounds of testing that involved eight candidate SR model forms (11.1 in Appendix 1), the LRB & RRB models consistently ranked well. Among the recursive models, preference was given to the Larkin form (LRB) as it can replicate Ricker non-cyclic “behavior” along with cyclic patterns and delayed density dependence. (Step 2, Figure A)

Models other than the LRB model were considered if (Step 3, Figure A):

1. recursive model fits were poor (this was not the case for any of our stocks of concern)
2. one of the other candidate models consistently ranked better, or
3. top rankings repeatedly switched back and forth between the Larkin recursive model (LRB) and another model.

The Larkin recursive (LRB) model was exclusively used for the rest of the analysis if it was the only model that ranked well for a DU (step 3, Figure A). If other models also ranked well, then a secondary evaluation was performed.

This secondary evaluation (Steps 4-6, Figure A) consisted of running forward projections with the remaining candidate SR models and checking the proportion of simulations that met the Recovery Target #1 criteria described in section 5.2. If the results were similar to what the recursive Bayesian Larkin model (LRB) obtained, then the LRB model was the only one used. Otherwise, the models were averaged using a technique where half the MCMC samples used for forward simulations came from each SR model. Plots similar to the grids shown in Appendix 3 were used for model comparison. For the candidate models being considered for a DU, comparisons were made between the ER values that produced a change in the Intergovernmental Panel on Climate Change categorization (Table 7) for Recovery Target #1 at productivity values of -50% to +30% in 10% increments. If the resulting ER values for two candidate models were more than 5% apart, then the candidate models were considered different enough to use both.

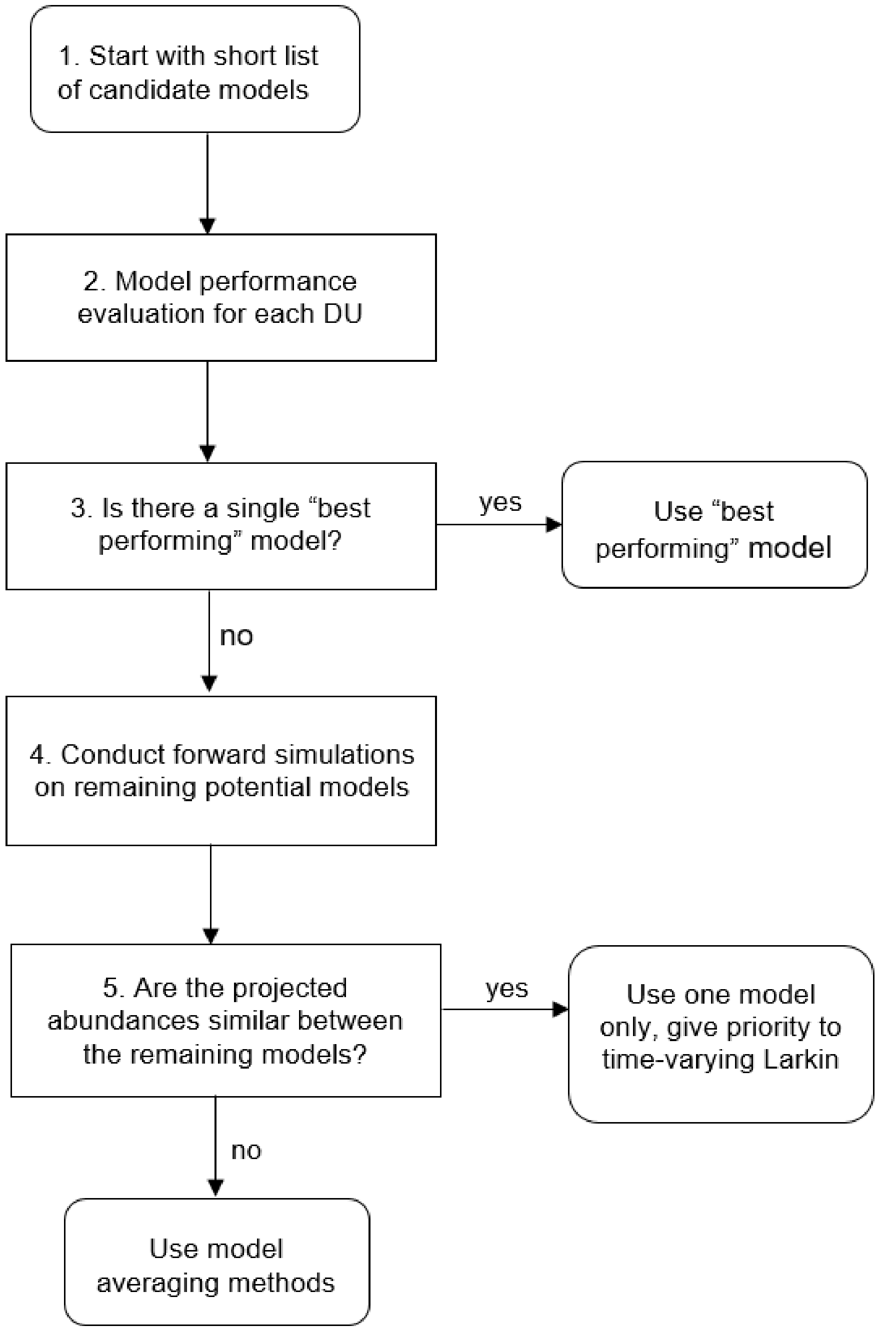

Figure A. Flowchart of the process employed to select stock-specific RPA simulation models.

5.3.4. Results: stock-specific model selection

Table 6 shows the selected model forms for each DU's simulations. The recursive Bayesian Larkin model (LRB) was used for all DUs, but for some DUs either the recursive Bayesian Ricker (RRB) or Ricker 5 Generation (R5Gen) forms were also used.

Table 6. Selected model form(s) for each DU.

Model Form	DUs Modelled
recursive Bayesian Larkin model (LRB)	Early Stuart, Bowron, Portage, Weaver, Raft* (DU 20, 2, 17, 10, 11)
recursive Bayesian Larkin model (LRB) *and* recursive Bayesian Ricker model (RRB)	Quesnel, Upper Barriere, Stellako*, Birkenhead* (DU 16, 14, 7, 12)
recursive Bayesian Larkin model (LRB) *and* non-recursive Bayesian Ricker model using 5 generations of stock-recruitment estimates (R5Gen)	Late Stuart (DU 21)

Note that these models were different from those used in the Grant et al. (2020*)* WSP status re-assessment of Fraser Sockeye. Grant et al. (2020) used Larkin models for cyclic stocks and Ricker models for the rest. Their purpose was to identify abundance benchmarks to use in order to identify the current WSP status. The objective here was for the stock-recruit models to represent DU behavior and project abundance into the near future. The models were also different from the approach taken by Pestal et al. (2012), who used the Larkin model for all DUs, as the objective in that paper was to represent stocks over the longer term (12 generations).

5.4. ELEMENT 13 (PART 2): PROJECT EXPECTED POPULATION TRAJECTORIES OVER A SCIENTIFICALLY REASONABLE TIME FRAME (MINIMUM OF 10 YEARS), AND TRAJECTORIES OVER TIME TO THE POTENTIAL RECOVERY TARGET(S), GIVEN CURRENT [WILDLIFE SPECIES] POPULATION DYNAMICS PARAMETERS – POPULATION MODELS: FORWARD SIMULATION

5.4.1. Overview

The main component of the forward simulation used fixed ERs as the primary lever to assess impacts on the recovery potential of the DUs, with sensitivity analyses focused on the productivity. Two caveats bear repeating: first, section 5.1 noted that fisheries are not the only source of adult mortality and simulation results need to be interpreted as such, and second, as stated in section 3, fisheries that target Fraser River Sockeye salmon typically harvest a mix of Fraser Sockeye DUs and management of such fisheries are based on HCRs that apply to SMUs that consist of multiple DUs. The exception is the Early Stuart SMU which only contains the Early Stuart DU (DU20).

While this paper was focused on individual DUs, it is unlikely that fisheries will shift to individual stock management. For determining the effects of more realistic management measures we recommend combining the work conducted here with insights that could be obtained from a model that more fully integrates actual management issues and practices. The DFO uses such a management model to evaluate the effects of aggregate harvest control rules on individual DUs (Pestal et al. 2012). The Pestal et al. (2012) management model was not used in this assessment as it includes additional factors that would confound the basic question being asked by the RPA terms of reference. These additional factors include: catch allocations, fisheries with management constraints and SMU-level harvest control rules that change with cycle year and require annual estimates of abundance and en-route mortality rates to determine annual allowable exploitation rates.

5.4.2. Methods: RPA simulation model

To assess the recovery potential of each stock we simulated the trajectories of spawner abundances using the SR models listed in Table 6. These models looped through the following steps:

1. For each stock, start with observed spawner abundance. The preliminary estimate for 2018 was the last available year.
2. Calculate total recruits generated from each brood year, applying multiplicative log-normal error in the estimation procedure.
3. Calculate run size for each return year. A fixed age proportion was assumed, based on the average proportion of age 4 returns from 1980 to current, as was used for annual run size forecasts (Grant and MacDonald 2012).
4. Calculate the spawner abundance for each return year by applying a fixed exploitation rate and a stochastic en-route mortality rate resampled from observed values.
5. Repeat steps 2-4 for 3 generations (i.e., 12 years).

Appendix 4 (14.4-14.5) documents the model code.

5.5. ELEMENT 15: ASSESS THE PROBABILITY THAT THE POTENTIAL RECOVERY TARGET(S) CAN BE ACHIEVED UNDER CURRENT RATES OF POPULATION DYNAMICS PARAMETERS, AND HOW THAT PROBABILITY WOULD VARY WITH DIFFERENT MORTALITY (ESPECIALLY LOWER) AND PRODUCTIVITY (ESPECIALLY HIGHER) PARAMETERS

5.5.1. Results: modelled stocks

See Appendix 3 (section 13) for plots.

For DUs that spawn upstream of the Big Bar landslide, an en-route mortality in 2019 of 99.5% was applied using information available in early August (i.e., 0.5% of the total post-fishery run arrives on the spawning grounds). This was considerably higher than some of the Big Bar landslide passage estimates for later in the season (early September). In this section, we present the best case scenario for years after 2019 by assuming that en-route mortality from 2020 onward returns to “normal”. The basis for this scenario was the possibility that the obstruction could be cleared over the winter of 2019, with no lingering passage or intergenerational effects.

Simulation results are presented as the percentage of the 5,000 forward simulations that met Recovery Target #1 and #2. To facilitate presentation and discussion of results, we used the likelihood outcome categories and descriptions defined by the Intergovernmental Panel on Climate Change (IPCC) (Mastrandrea et al. 2010), shown in Table 7.

Table 7. IPCC Likelihood Scale (from Mastrandrea et al 2010)

Term	**Likelihood of the Outcome**
Virtually Certain	99-100% probability
Very Likely	90-100% probability
Likely	66-100% probability
About As Likely As Not	33-66% probability
Unlikely	0-33% probability
Very Unlikely	0-10% probability
Exceptionally Unlikely	0-1% probability

Table 8 summarizes the results for element 15. Stocks in this table and Appendix 3 are grouped into the following:

1. EN/TH stocks that spawn downstream of Big Bar landslide (plots in 13.1 of Appendix 3),
2. EN/TH stocks that spawn upstream of Big Bar landslide (plots in 13.2 of Appendix 3),
3. Special Concern stocks (plots in 0 of Appendix 3).

The numbers shown in the last two columns of Table 8 show the maximum ER that corresponds to a categorization of "likely" to have reached Recovery Target #1 (second from last) or Recovery Target #2 (last column), where "likely" uses the IPCC likelihood categories described in Table 7 (i.e., 66-100%). That is, when looking at the grids in Appendix 3 that summarize the simulation results, we examined the column of values corresponding to the current productivity level (i.e., "Productivity Change" = 0) to locate the value of 66 (i.e., 66%) or next larger number, then read the ER corresponding to that row from the left hand side of the grid. If 66 was not in the column, an "NA" for "not applicable" was returned.

With the exception of Stellako* (DU7) there were no ERs that would result in a Likely to reach Recovery Target #2 after three generations, at current productivity for any of the stocks that were designated as Endangered, Threatened, or Special Concern (Table 8). However, Quesnel (DU16) and Stellako* (DU7) were Likely to reach Recovery Target #1 with ERs greater than zero at current productivity (25% for Quesnel and 55% for Stellako*, DU 16, 7).

Table 8. Summary of simulation results at current productivity. Last four columns: A = the maximum exploitation rate that was associated with a DU being "Likely" to reach Recovery Target #1 (i.e., maximum ER that results in 66% of the projections reaching Recovery Target #1); B = the percentage of projections that met Recovery Target #1 with no additional exploitation rate (at current productivity); C = the maximum exploitation rate that was associated with a DU being "likely" to reach Recovery Target #2; D = the percentage of projections that met Recovery Target #2 with no additional exploitation rate.

Common Name	***DU Name and Number***	***COSEWIC Status***	***Spawn above Big Bar***	***A. max ER that meets Recovery Target #1***	***B. % of projections that meet Recovery Target #1 at ER = 0%***	***C. max ER that meets Recovery Target #2***	***D. % of projections that meet Recovery Target #2 at ER = 0%***
Early Stuart	*Takla-Trembleur-Estu DU 20*	*EN*	*Y*	*NA*	*3*	*NA*	*0*
Bowron	*Bowron-ES DU 2*	*EN*	*Y*	*NA*	*20*	*NA*	*1*
Taseko	*Taseko-ES DU 22*	*EN*	*Y*	*not modelled*			
Upper Barriere	*North Barriere-ES DU 14*	*TH*	*N*	*NA*	*50*	*NA*	*22*
Quesnel	*Quesnel-S DU 16*	*EN*	*Y*	*25*	*85*	*NA*	*16*
Late Stuart	*Takla-Trembleur-Stuart-S DU 21*	*EN*	*Y*	*0*	*66*	*NA*	*18*
Widgeon	*Widgeon (River-Type) DU 24*	*TH*	*N*	*not modelled*			
*Raft**	*Kamloops-ES DU 11*	*SC*	*N*	*NA*	*50*	*NA*	*18*
*Stellako**	*Francois-Fraser-S DU 7*	*SC*	*Y*	*55/35*	*99*	*5*	*72*
Portage	*Seton-L DU 17*	*EN*	*N*	*NA*	*40*	*NA*	*14*

Common Name	*DU Name and Number*	*COSEWIC Status*	*Spawn above Big Bar*	*A. max ER that meets Recovery Target #1*	*B. % of projections that meet Recovery Target #1 at ER = 0%*	*C. max ER that meets Recovery Target #2*	*D. % of projections that meet Recovery Target #2 at ER = 0%*
Weaver Creek	*Harrison (U/S)-L DU 10*	*EN*	*N*	*NA*	*56*	*NA*	*26*
*Birkenhead**	*Lillooet-Harrison-L DU 12)*	*SC*	*N*	*0*	*67*	*NA*	*24*

Endangered & threatened - not affected by Big Bar landslide

Upper Barriere/Fennell (North Barriere-ES DU14), Portage (Seton-L DU17), Weaver (Harrison (U/S)-L DU10) – plots in Appendix 3 (13.1).

Under current productivity assumptions and at an ER of 0%, Upper Barriere, Portage, and Weaver were all As Likely As Not to reach Recovery Target #1 and Unlikely to reach Recovery Target #2 in the next three generations.

Endangered & threatened - affected by Big Bar Landslide

Early Stuart (Takla-Trembleur-EStu DU20), Bowron (Bowron-ES DU2), Quesnel (Quesnel-S DU16), Late Stuart (Takla-Trembleur-Stuart-S DU21) – plots in Appendix 3 (13.2).

Under current productivity assumptions and even with an ER of 0%, Bowron was Unlikely to reach Recovery Target #1 and Early Stuart was Very Unlikely to reach Recovery Target #1. Both Bowron and Early Stuart were Exceptionally Unlikely to reach Recovery Target #2.

In contrast, Quesnel and Late Stuart were both Likely to reach Recovery Target #1 under current productivity conditions, though both were Unlikely to reach Recovery Target #2.

Note that the upper WSP benchmark for Quesnel shown in Table 4 of 1.3 million spawners is well above the average 1948-2018 spawners of 350,000, but below the largest four year average of 1.7 million. For Late Stuart, the WSP benchmark of 590,000 spawners is well above the 1949-2018 spawner average of 130,000 and also larger than the largest four year spawner average of 520,000.

Special Concern

Raft (Kamloops-ES DU11), Birkenhead* - (Lillooet-Harrison-L DU12), Stellako* (Francois-Fraser-S DU7)* – plots in Appendix 3 (13.3).

Under current productivity assumptions and an ER of 0%, Raft* was As Likely as Not to reach Recovery Target #1 and Unlikely to reach Recovery Target #2 in the next three generations. While Birkenhead* was Likely to reach Recovery Target #1 under these circumstances, an increase in ER to 5% makes it As Likely as Not to reach Recovery Target #1. This equates to a coin toss as to whether the condition of Raft* and Birkenhead* stays at Special Concern or gets downgraded to Endangered or Threatened over the next three generations, even at low exploitation rates.

Under current productivity assumptions and an ER of 0%, Stellako* was Likely to reach Recovery Target #2 and Virtually Certain to reach Recovery Target #1 in the next three generations. Note that Stellako* is a DU that spawns upstream of the Big Bar landslide.

General results notes – modelled stocks

The limiting factor for the DUs that were Unlikely to reach Recovery Target #1 falls into two categories: DUs spawning upstream of the Big Bar landslide were limited by the S_{gen} criteria, whereas the slope criteria limited the DUs spawning below the Big Bar landslide. There were two slope criteria, depending on whether a DU has more than or less than 10,000 mature individuals in the last generation (Table 5 in section 5.2.3).

5.5.2. Stocks without stock-recruit time series

Taseko (Taseko-ES DU22)

The Taseko system flows into the Chilko River, which subsequently becomes the Chilcotin River and flows into the Fraser River downstream of Williams Lake. Taseko Sockeye were categorized as an Early Summer DU and so migrates earlier than Chilko Sockeye. They are difficult to distinguish from co-migrating DUs such as Bowron (DU2) and Quesnel (DU16) based on their DNA, and so difficult to estimate in migratory areas. Glacial silt prevents visual surveys of spawning abundance, so carcass expansion methods have been used for many years. Bear predation can affect the ability of Stock Assessment crews to obtain carcasses. Estimates since 2013 have improved due to the use of DIDSON hydroacoustic technology.

Taseko spawns upstream of the Big Bar landslide. In the years when hydroacoustics were not used for assessment, the spawner numbers should be interpreted as minimum estimates due to the difficulty associated in visually assessing this system (K. Benner, DFO Stock Assessment, Kamloops, BC, pers. comm.). The average number of *effective female* spawners (EFS) was 1400 fish (1952-2018). There was a drop in the number of EFS in the early 1990s that has persisted to the present. This drop does not appear to be driven by exploitation rates, which have been variable, but declining since the 1980s. (Figure 41 in Appendix 3)

Widgeon (Widgeon (River-Type) DU24)

Widgeon Creek and Widgeon Slough comprise a small watershed that flows into the Pitt River just below the outlet of Pitt Lake. Widgeon Sockeye are the most genetically distinct of Fraser Sockeye stocks as determined by DNA analyses. Until 2012, it was considered a Late-run DU. Since 2012, it has been managed as part of the Summer run along with Harrison Sockeye, since it shares characteristics of timing and age (more sub-1s than other Fraser stocks) with the larger Harrison DU. Because of its small abundance in migratory areas, Harrison Sockeye are used as a proxy to predict its migration timing. Estimates of spawning abundance were of poor quality because of the tendency for carcasses to be washed out of the system during tidal changes. Estimates of spawner abundance were likely underestimates, but unlike Taseko (DU 22), can likely be used as an index of the true abundance (K. Benner, pers. comm.). The population size of Widgeon Sockeye was almost certainly below COSEWIC criterion D levels, but it has maintained this small population size over time and across a wide range of ERs.

Widgeon spawning grounds are well below the Big Bar landslide. The long term average EFS was 331 (1952-2018). There was a sharp drop from a pre 1990 EFS of 436 to a post 1990 EFS of 178. This drop does not appear to be caused by fishery mortalities as the average ER in the corresponding time period also dropped from 75% to 33%. (Figure 20 in Appendix 3)

Note that the lack of obvious cause-and-effect between EFS and ERs does not mean that declines in Taseko and Widgeon were not due to human-induced mortality, only that the declines do not appear to be solely caused by fisheries that targeted co-migrating Sockeye.

6. SCENARIOS FOR MITIGATION OF THREATS AND ALTERNATIVES TO ACTIVITIES

6.1. ELEMENT 19: ESTIMATE THE REDUCTION IN MORTALITY RATE EXPECTED BY EACH OF THE MITIGATION MEASURES OR ALTERNATIVES IN ELEMENT 16 AND THE INCREASE IN PRODUCTIVITY OR SURVIVORSHIP ASSOCIATED WITH EACH MEASURE IN ELEMENT 17

6.1.1. Overview

Some mitigation measures lend themselves to quantitative assessment more than others. For example, the effects of adding a spawning channel would be easier to quantify than effects due to improved data or models. Due to the large number and types of mitigation projects that could be undertaken, with one exception this analysis was simplified by assessing the impacts of increased productivity without naming the specific measure(s) that would have led to such improvements.

The exception relates to the Big Bar landslide that blocked the adult migration of Fraser River Sockeye (and other species) in 2019. Its effect on future migrations is currently unknown. This scenario is an example of how the mitigation measures at the Big Bar site could be implemented in the model to assess its effect on populations that spawn upstream of the site.

6.1.2. Methods: Alternative future productivity SR models

To simulate future productivity scenarios, the median alpha (α_{med}) of the 10,000 MCMC samples described in section 5.3.2 was identified. For each one percent change in the productivity value of interest (ρ), a new median alpha value was calculated:

$$\alpha_{new} = \alpha_{med} + (\alpha_{med} * \rho)$$

The 5,000 MCMC samples used in the forward simulations were selected so that half were drawn from samples with alpha values greater than α_{new} and half from those less than α_{new}.

A range of future productivity change was modelled of -50% to +30% from current. A 50% reduction was chosen as the bottom range as 50% declines in estimated productivity has been in the range of observed declines for some stocks over three generations. While we believe, based on trends observed in the alpha plots shown in section 11.3 (Appendix 1), that increases in productivity in the near future are unlikely for these stocks, a modest increase in productivity was included to demonstrate the potential magnitude of impacts that increases in productivity and/or mitigation measures could have.

6.1.3. Methods: Big Bar Landslide example mitigation scenario

Our “base case” scenario was based on the assumption that the effects of the slide on affected DUs was not moderated during the first year (2019) but that normal low water levels during the first winter allowed the obstruction to be fully cleared, perhaps by the use of explosives combined with the force of moving water during spring freshet (2020) to remove debris. Thus, in the model the first year was subject to the full impact of the Big Bar slide (99.5% mortality) with subsequent years assigned the normal en-route mortality for element 15 (section 5.5).

The mortality rate of 99.5% was higher than the mortality rates reported in-season at Big Bar (early in-season estimates were >95%, falling to ~55% in early September due to mitigation efforts and lower discharge rates). We chose to use 99.5% mortality on 5,000 simulated run sizes that were more reflective of the pre-season forecast. This was in contrast to the in-season estimates which were:

1. mortality estimates for fish passage for the Big Bar landslide site only, not mortalities prior the site or from above the site to the spawning grounds,
2. applied to the in-season return, that were well below the 10th percentile of the forecast run size range, and
3. occurring in a year when en-route mortality to the spawning grounds was anticipated to be higher than average because daily in-river water temperatures were consistently greater than average.

A more nuanced hypothetical example to show how alternative mitigation scenarios could be modelled was also presented. The “fishway example” corresponds to a situation in which the use of explosives to clear the obstruction during the first winter was not feasible, and instead a fishway is installed over the subsequent three winters. In the first winter (2020), larger rocks are manipulated to ease fish passage, which reduces the mortality rate from 99.5% in 2019 to 80% in 2020. In the second winter, additional rock manipulations decrease the mortality rate further to 75%. After the third winter, the fishway is fully functional and the mortality rate associated with the fishway drops to 20%. Note that the mortality associated with Big Bar passage was modelled in addition to the historical en-route mortality.

The mortality rates associated with rock manipulation and fishway were purely hypothetical and could as easily been associated with two winters of relatively minor rock work and a large rock removal event in the third winter.

We also present a series of sensitivity analyses in which the 99.5% Big Bar mortality persists for more than 1 year. This series helps to cast light on the importance of dominant cycle years for cyclic stocks and the cumulative effect of catastrophic mortality for multiple years in a row.

6.2. ELEMENT 20: PROJECT EXPECTED POPULATION TRAJECTORY (AND UNCERTAINTIES) OVER A SCIENTIFICALLY REASONABLE TIME FRAME AND TO THE TIME OF REACHING RECOVERY TARGETS, GIVEN MORTALITY RATES AND PRODUCTIVITIES ASSOCIATED WITH THE SPECIFIC MEASURES IDENTIFIED FOR EXPLORATION IN ELEMENT 19. INCLUDE THOSE THAT PROVIDE AS HIGH A PROBABILITY OF SURVIVORSHIP AND RECOVERY AS POSSIBLE FOR BIOLOGICALLY REALISTIC PARAMETER VALUES

6.2.1. Results: Alternative future productivity scenarios

See Appendix 3 (13.1-13.3).

Endangered & threatened - not affected by Big Bar landslide

Upper Barriere/Fennell (North Barriere-ES DU14), Portage (Seton-L DU17), Weaver (Harrison (U/S)-L DU10) – plots in Appendix 3 (13.1).

Upper Barriere was As Likely As Not to reach Recovery Target #1 throughout the entire productivity range of -50% to +30% at 0-5% ER. At current productivity, Upper Barrier was

Unlikely to reach Recovery Target #2 at ERs of 25% or more. Upper Barriere was Unlikely to Very Unlikely to reach Recovery Target #2 over all productivities and ERs modelled.

Portage was Unlikely to reach Recovery Target #1 over most of the combinations of productivity and ERs modelled. At current productivity, Portage was Unlikely to reach Recovery Target #1 at ERs of 20% or more. Portage was Very Unlikely to reach Recovery Target #2 over most of the ERs & productivities modelled.

Weaver was As Likely As Not to reach Recovery Target #1 over a wide range of productivities and ERs modelled. At current productivity, Weaver was Unlikely to reach Recovery Target #1 at ERs of 50% or more. Weaver was Unlikely to Very Unlikely to reach Recovery Target #2 over all the productivities and ERs modelled.

Endangered & threatened - affected by Big Bar Landslide

Early Stuart (Takla-Trembleur-EStu DU20), Bowron (Bowron-ES DU2), Quesnel (Quesnel-S DU16), Late Stuart (Takla-Trembleur-Stuart-S DU21) – plots in Appendix 3 (13.2).

Early Stuart was Very Unlikely to reach Recovery Target #1 across the range of productivities modelled. At ERs much larger than 10-15%, Early Stuart was Exceptionally Unlikely to reach Recovery Target #1. At all ERs and productivity ranges modelled, Early Stuart was Exceptionally Unlikely to reach Recovery Target #2.

Across the range of productivities modelled and 0% ER, Bowron was Unlikely to reach Recovery Target #1. As ERs increase under current productivity, Bowron becomes Very Unlikely (at 20% ER) and then Exceptionally Unlikely (50% ER) to reach Recovery Target #1. Bowron was Exceptionally Unlikely to reach Recovery Target #2 for over most of the productivities and ERs modelled.

At 0% ER across all productivity ranges, Quesnel was Likely to reach Recovery Target #1. At currently productivity, the likelihood categories change as ER increases: to As Likely As Not at 30% ER, Unlikely at 55% ER, Very Unlikely at 70% ER, and Exceptionally Unlikely at 85% ER. Quesnel was Unlikely to Exceptionally Unlikely to reach Recovery Target #2 over the range of productivities and ERs modelled.

There were a small set of conditions where Late Stuart was Likely to reach Recovery Target #1 – generally lower ERs and higher productivities. At current productivity, Late Stuart changes from being Likely to reach Recovery Target #1 with 0% ER to As Likely As Not at 5% ER then Unlikely at 40% ER, Very Unlikely at 65% ER and Exceptionally Unlikely at 85% ER. Late Stuart was Unlikely to Exceptionally Unlikely to reach Recovery Target #2 over the range of productivities and ERs modelled.

Special Concern

Raft (Kamloops-ES DU11), Birkenhead* - (Lillooet-Harrison-L DU12), Stellako* (Francois-Fraser-S DU7)* – plots in Appendix 3 (13.3).

Raft* was Unlikely to reach Recovery Target #1 over a wide range of productivities and ERs modelled. At current productivity, Raft* changes from being As Likely As Not to reach Recovery Target #1 to Unlikely at 20% ER, then Very Unlikely at 45% ER, and Exceptionally Unlikely at 65% ER. Raft* was Unlikely to Exceptionally Unlikely to reach Recovery Target #2 over the range of productivities and ERs modelled.

There were a small set of conditions where Birkenhead* was Likely to reach Recovery Target #1 – generally lower ERs and higher productivities. At current productivity, Birkenhead* changes from Likely to reach Recovery Target #1 to As Likely As Not at 5% ER, then Unlikely at 40% ER, Very Unlikely at 65% ER and Exceptionally Unlikely at 80% ER. Birkenhead* was Unlikely to Exceptionally Unlikely to reach Recovery Target #2 over the range of productivities and ERs modelled.

Results for Stellako* cover the entire likelihood range. At current productivity and 0% ER, Stellako* was Virtually Certain to reach Recovery Target #1, this declines to Very Likely at 5% ER, Likely at 40% ER, As Likely As Not at 60% ER, Unlikely at 75% ER, Very Unlikely at 85% and Exceptionally Unlikely at 90% ER. There were a limited set of conditions where Stellko was Likely to reach Recovery Target #2 – generally lower ERs and higher productivities. At current productivity, Stellako* was Likely to reach Recovery Target #2 at 0-5% ER, was As Likely As Not at 10% ER, Unlikely at 40% ER, Very Unlikely at 55% ER, and Exceptionally Unlikely at 75%.

6.2.2. Results: Big Bar landslide scenarios

The four panel grid plots shown in Appendix 3 (13.2-13.3) for the Big Bar stocks shows the likelihood of the stock reaching Not EN/TH under the following scenarios:

- 2 year blocked passage – 99.5% mortality in 2019 & 2020, with the rest of the years at “normal” en-route mortality
- 3 years blocked passage – 99.5% mortality in 2019-2021
- 4 years blocked passage – 99.5% mortality in 2019-2022
- Fishway – the fishway example described in section 6.1.3, of mortality dropping from 99.5% in 2019, 80% in 2020, 75% in 2021, and finally 20% in 2022 and beyond.

The description in the rest of this section will focus on the fishway scenario, as the other scenarios were mostly provided as a sensitivity analysis.

Endangered & threatened - affected by Big Bar Landslide

Early Stuart (Takla-Trembleur-EStu DU20), Bowron (Bowron-ES DU2), Quesnel (Quesnel-S DU16), Late Stuart (Takla-Trembleur-Stuart-S DU21) – plots in Appendix 3 (13.2).

Across the entire range of productivities and ERs, Early Stuart was Exceptionally Unlikely to reach Recovery Target #1 under the fishway scenario.

With the exception of the single set of conditions when ER was 0% and productivity increased by 30%, Bowron was Very Unlikely to Exceptionally Unlikely to reach Recovery Target #1 under the fishway scenario.

In the fishway scenario, there were a small set of conditions where Quesnel was Likely to reach Recovery Target #1 – generally lower ERs and higher productivities. At current productivity, Quesnel was Likely to reach Recovery Target #1 at 0% ER, As Likely As Not at 5% ER, Unlikely at 40% ER, Very Unlikely at 60% ER and Exceptionally Unlikely at 80% ER.

There were no conditions under which Late Stuart was Likely to reach Recovery Target #1 in the fishway scenario. However, at lower ERs and productivities near current, it was As Likely As Not that Late Stuart would reach Recovery Target #1. At current productivity, Late Stuart was Unlikely to reach Recovery Target #1 at an ER of 10% or higher.

Special Concern

Stellako (Francois-Fraser-S DU7)* – plots in Appendix 3 (13.3.3).

At 15% ER or lower, across the full range of productivities modelled, Stellako* was Likely to Very Likely to reach Recovery Target #1 under the fishway scenario. At current productivity, Stellako* was Very Likely to reach Recovery Target #1 at 0-5% ER, Likely at 10% ER, As Likely

As Not at 40% ER, Unlikely at 65% ER, Very Unlikely at 75% ER, and Exceptionally Unlikely at 85% ER.

6.3. ELEMENT 21: RECOMMEND PARAMETER VALUES FOR POPULATION PRODUCTIVITY AND STARTING MORTALITY RATES AND, WHERE NECESSARY, SPECIALIZED FEATURES OF POPULATION MODELS THAT WOULD BE REQUIRED TO ALLOW EXPLORATION OF ADDITIONAL SCENARIOS AS PART OF THE ASSESSMENT OF ECONOMIC, SOCIAL, AND CULTURAL IMPACTS IN SUPPORT OF THE LISTING PROCESS

We highly recommend that the lead author of this document be consulted before any exploratory analysis of economic, social and cultural impacts, if such analysis is intended to be based on results in this paper. The focus and design of this analysis was specific to individual DUs and short-term outcomes, so our results may not easily contribute to analyses involving mixed stock fishery outcomes over longer time frames. As noted in section 3, fisheries on Fraser Sockeye are managed at the mixed DU SMU level, whereas this analysis was focused at the single DU level. In addition, there is considerable uncertainty associated with the immediate and long term impacts of the Big Bar landslide. As well, there were several key uncertainties (section 7) that additional analysis would need to take into account.

Table 9 compares the average productivity in the last generation (brood years 2010-2013) to previous generations and to the average productivity over the entire time period of productivity estimates available for each DU. These results show the degree to which productivity has been changing.

Table 9. Productivity change compared to recent (2010-2013 brood year average)

%change vs 2010-2013 (BY)	1998-2001	2002-2005	2006-2009	all years
Upper Barriere (DU14)	-62%	-52%	-40%	-64%
Portage (DU17)	-31%	-17%	-13%	-39%
Weaver (DU10)	-43%	-35%	-28%	-43%
Early Stuart (DU20)	-23%	-24%	-47%	-63%
Bowron (DU2)	-39%	-31%	-27%	-60%
Quesnel (DU16)	-34%	-17%	-6%	-45%
Late Stuart (DU21)	-48%	-32%	-23%	-60%
Raft* (DU11)	-31%	-18%	-7%	-24%
Birkenhead* (DU12)	-59%	-51%	-47%	-67%
Stellako* (DU7)	-21%	-10%	-8%	-28%

Table 10 compares the average spawners in the last generation (2015-2018 return year) to the S_{gen} value from Grant et al (2020). S_{gen} is the "spawner abundance that will result in recovery to S_{MSY} in one generation in the absence of fishing under equilibrium conditions" (Holt et al. 2009). Being below S_{gen} was one of the WSP metrics associated with Red status and it is generally considered desirable to stay above this value. Similar to the upper WSP abundance benchmarks described in section 5.2.2, some of these values were averaged from those provided in Grant et al *(*2020*)*. Note that there is a discrepancy in the units being used, in that total spawners are used for the average spawner numbers reported below and in the model, while total effective spawners were used to calculate S_{gen}.

Table 10. Comparison of the average spawners in the last generation (2015-2018 return year) to the S_{gen} value from Grant et al. (2020).

Common Name (DU number)	**Sgen**	**avg Spawners 2015-2018**	**avg Spawners 2015-2018 as % of Sgen**
Upper Barriere (DU14)	640	23,686	3701%
Portage (DU17)	2,193	26,283	1198%
Weaver (DU10)	10,731	1,417	13%
Early Stuart (DU20)	107,896	24,177	22%
Bowron (DU2)	5,148	3,158	61%
Quesnel (DU16)	192,267	244,348	127%
Late Stuart (DU21)	126,384	69,924	55%
Raft * (DU11)	4,958	8,065	163%
Birkenhead* (DU12)	14,932	28,765	193%
Stellako* (DU7)	*24,256*	*99,888*	*412%*

7. KEY UNCERTAINTIES & KNOWLEDGE GAPS

7.1. KEY UNCERTAINTIES

One of the key uncertainties with using stock-recruit models is that the past is used to predict the future. While this can be an effective method in some situations, for most of the Endangered, Threatened, and Special Concern stocks examined here, the estimates of current productivity were not reflected in earlier time varying estimates of productivity (11.2). Alternative future productivities have only been explored on a very coarse scale in this analysis.

Key biological process uncertainties affecting this analysis include productivity, in-river mortality rates, and pre-spawn mortality rates. A range of alternative future productivities has been included in the modelling, but explicitly modelled changes to in-river mortality rates outside of the Big Bar scenarios were not included. It was assumed that changes to in-river en-route mortality rates (relative to the base period of 2002-2018 used for modelling) will be incorporated into the allowable harm values based on annual pre-season and in-season information (see section 5.1). If pre-spawn mortality rates remain in the historical range, then pre-spawn mortality has been incorporated into the uncertainty of the stock-recruit parameter estimates used in this analysis.

The key management process uncertainties of assessment error (estimates of run size, catch and spawning escapement) and outcome uncertainty (i.e., implementation error) were not included in this assessment.

In addition, there are uncertainties associated with the collection of biological data (run size, recruits, escapement, in-river mortality, pre-spawn mortality, age proportions, etc.) that tend to increase at lower abundances (7.1.1). Some of these uncertainties were incorporated through the Bayesian methods employed.

7.1.1. Data

Although the models capture the variability and uncertainty inherent in the data, the datasets themselves contain uncertainties such as error estimating run size, catch, exploitation rate and spawning abundance that were not integrated into the SR models. Reported uncertainties in performance metrics are therefore likely underestimated. This analysis was also subject to a known bias towards overestimating productivity (errors in variables bias) that is exacerbated at low run sizes, because methods used to estimate run size and spawning escapement become less precise. In this analysis, it results in a tendency to be overly optimistic with respect to the degree and speed of recovery.

7.1.2. Stock-recruit models

Despite cyclic patterns being well documented for some Fraser stocks, there is no consensus as to what causes them. In this analysis, the focus was on modelling the cyclic patterns without attempting to model underlying mechanisms. The Larkin form of SR relationship is appropriate when modelling cyclic patterns in Sockeye abundance (DFO 2006) over many generations, and has been used as the default SR model for longer term (48 year) forward simulation models (Pestal et al. 2011). However, when using the same starting conditions, both the Ricker and Larkin model forms will generate similar abundances if the modelling time frame was 2-3 Sockeye generations into the future. Only in longer term analyses will the two stock-recruit model forms diverge (Huang 2014).

7.1.3. Recovery Targets

The recovery target methodology proposed for the RPA was based on COSEWIC criteria and WSP methodology. While the Recovery Targets refer to COSEWIC and WSP processes, the computational methods in this paper do not capture the nuances in these expert-driven approaches. Both COSEWIC and WSP status determinations were made during multi-day meetings by subject matter experts. Criteria were outlined in COSEWIC (2018) and Holt et al. (2009), but were not translatable into a simple repeatable algorithm.

7.1.4. Mitigation and mortality

Our ability to quantitatively assess possible mitigation projects was limited, not only because of the sheer number of possible actions for the DUs being assessed, but also because it was unlikely that we would have much confidence in our calculated outcomes for any specific action other than decreasing fishing mortality and perhaps some hatchery enhancement activity. Instead, this report employed a more generalized approach, increasing and decreasing productivity by different amounts relative to the estimate of current productivity. Model runs with higher productivity would represent cases where mitigation efforts or environmental changes resulted in increased productivity, while runs with lower productivity represent cases where stress of any kind caused the opposite impact. As specific mitigation measures are developed in the future, a range of DU- and project- specific productivity changes should be developed and could then be compared to our range of projected outcomes.

Sockeye mortality was included in the models but, similar to the treatment of productivity, the modelled mortality represents a variety of possible unspecified sources such as harvest, en-route mortality, redd dewatering and changes in predation rates (see 5.1.1). We focused on productivity because COSEWIC criterion B, which is concerned with small distribution ranges and the decline or fluctuation in distributions, was not flagged by COSEWIC as a reason for EN/TH/SC status for any Fraser Sockeye DUs (COSEWIC 2017).

In late June 2019, a large landslide was discovered to have occurred in the Fraser River at a location near Big Bar, BC. Preliminary investigations indicated that the slide actually occurred in the autumn of 2018. The slide fully blocked the natural passage of salmon in the summer of 2019 for a number of weeks. At the time of this report, the full impact of the slide on the migration and reproduction of Fraser salmon stocks was unknown. However, a placeholder in the form of a high 2019 in-river mortality rate for stocks spawning upstream of the Big Bar landslide was included in the base case simulation model runs. The effects of potential future mitigation measures could not be assessed until water levels decreased in the winter. As such, any modelled effects from the slide or mitigation measures to compensate for the slide presented in this report are speculative.

7.1.5. Future productivity and impacts of a changing environment

Climate change, habitat degradation, human disturbance, forest fires and other aspects of the environment that affect Fraser Sockeye are rapidly changing. Some impacts can be anticipated in a qualitative sense, but quantitatively predicting the impact of the entire suite of interacting influences on all of the DUs in this analysis was beyond the scope of this report. Thus, in this report “recovery” was not meant to represent “recovery back to a time when 80% harvest rates were sustainable”. Instead, “recovery” was interpreted as a state where COSEWIC was likely to designate a DU as “Not At Risk”.

For the base case model runs we assumed that productivity had not remained constant over time and instead used estimates of recent productivity levels for population projections. Additional scenarios that explore both higher and lower productivity levels were included in this analysis. The productivity range modelled was not based on quantitative predictions of responses to environmental changes but was used as “what if” scenarios. While the agents that affect productivity likely operate on a longer time scale than the three generations assessed in this analysis, the changes have already begun and this analysis needs to consider their impact on recovery.

Reflecting on the potential impacts the environment has already had on the productivity and behavior of Fraser Sockeye, since 2001 Fraser Sockeye have: returned with the earliest timing on record, largest return, smallest return, largest diversion rate through the Johnstone Strait approach, smallest number of recruits per spawner, and disruption of the delayed migration pattern that Adams River Sockeye had reliably displayed since written records began. In 2019 alone, the preliminary estimate of the Fraser Sockeye return was the lowest since records began in 1893, almost halving the previous lowest return record set in 2016, and the upstream migration of a number of Fraser Sockeye DUs to their spawning grounds was blocked by a landslide in the river.

7.2. KNOWLEDGE GAPS

While currently not a gap for these DUs, we emphasize the importance of regular Stock Assessment programs for gathering the escapement data that is fundamental for conducting analyses such as the one presented in this paper. We are concerned about the erosion of resources available for these crucial programs in recent years.

Assessment programs, both for spawners and run size, were designed to decrease precision and effort at lower abundances. This results in higher uncertainty at lower abundances of the stock-recruit relationship and results in a stock-recruit curve that is shaped more by the large returns than the small ones. For the purposes of an RPA, what happens at these low abundances is of most concern and importance.

Data to build life-history type models that could incorporate mortalities at different life history stages are unavailable. This includes such basic information as freshwater versus marine survival rates for most Fraser Sockeye stocks.

The cumulative impacts of sub-lethal effects, such as release or escaping from fishing gear, disease, responses to changes in temperature at different life history stages, competition in the ocean, etc., have not been evaluated.

In addition to these overall knowledge gaps, there was a specific gap in the available data for Taseko and Widgeon. The small abundances of these stocks and Widgeon's downstream location relative to the Mission hydroacoustics site makes direct estimates of their returning abundance infeasible. For Taseko, estimates of spawning escapement have improved in some more recent years due to the use of hydroacoustic technology, compared to those obtained previously by carcass surveys which suffered due to the glacial nature of the system. Funding has not been provided to run a hydroacoustics-based assessment as part of DFO's regular suite of assessment programs.

8. ALLOWABLE HARM ASSESSMENT: PART ONE – MODEL RESULTS

8.1. ELEMENT 22: EVALUATE MAXIMUM HUMAN-INDUCED MORTALITY AND HABITAT DESTRUCTION THAT THE SPECIES CAN SUSTAIN WITHOUT JEOPARDIZING ITS SURVIVAL OR RECOVERY

The following definitions were taken from the DFO Guidance on Assessing Threats, Ecological Risk and Ecological Impacts for Species at Risk (2014):

Allowable harm - *Harm to the wildlife species that will not jeopardize its recovery or survival.*

Harm - *The adverse result of an activity where a single or multiple events reduce the fitness (e.g., survival, reproduction, growth, movement) of individuals*

Jeopardize - *To place a wildlife species or population in a situation where survival or recovery are at risk*

Recovery - *A return to a state in which the population and distribution characteristics and the risk of extinction are all within the normal range of variability for the wildlife species*

Survival - *The achievement of a stable or increasing state where a wildlife species exists in the wild in Canada and is not facing imminent extirpation or extinction as a result of human activity*

While the intention of the definition of "allowable harm" appears clear, the quantification of allowable harm is anything but. The nested Recovery Targets #1 and #2 were defined by a series of quantitative performance measures. However, the term "not jeopardize" contains the concept of determining a level of acceptable risk which was not quantified in the guidance document. With this in mind, the percentage of simulations that reached each Recovery Target under a wide range of ERs and future productivity levels were provided. In addition, the IPCC's likelihood categories have been applied to the model results as a qualitative method for describing the potential of reaching each Recovery Target.

The impacts of the Big Bar landslide to the 2019 return was still unknown at the time the model results were being generated in August 2019. Therefore the assessments of allowable harm for the DUs that spawn above the blockage can not be done based on the modelled outcomes presented in this paper. However, the *methods* described in this paper regarding how to assess Big Bar scenarios would not change and simulation assumptions can easily be updated with revised inputs. At the time of final paper submission, Near Final estimates of spawners to the grounds for each DU and preliminary estimates of en-route mortality for aggregations of fish above the DU level were available. Generally speaking, using 99.5% en-route mortality for Early Stuart (DU20) and Bowron (DU2) was fairly representative of observed outcomes, whereas it was overly pessimistic for the later migrating DUs (M. Hawkshaw, DFO Stock Assessment, Delta, BC, pers. comm.).

The discussion below focuses on the achievement of Recovery Target #1 as, with the exception of Stellako* (DU7), all of the DUs were modelled to be Unlikely (<33% of simulations) to Exceptionally Unlikely (<1% of simulations) to reach Recovery Target #2, even with 0% additional mortality by the end of the 12 year/three generation simulation as shown in Table 8 and Appendix 3. This convention is not to be interpreted to mean that being Likely to reach Recovery Target #1 in the next 12 years is equivalent to a DU being "recovered". It is worth remembering that the algorithm used in the simulations were highly simplified representations of the expert-driven COSEWIC and WSP processes.

This report covers elements 12, 13, 15, 19-21 (i.e., quantitative analysis of recovery targets, probability of achieving recovery targets, and mitigation effects) and summarizes how these elements would contribute to element 22 (i.e., allowable harm). A companion paper to be published at a later date will cover the remaining elements and provide the final allowable harm advice. **The allowable harm assessment in this document does not include the elements covering habitat, threats, and limiting factors and should not be interpreted as being the final allowable harm statement for these DUs.**

8.1.1. Quesnel and Stellako* (DU 16, 7)

While four DUs (Quesnel, Late Stuart, Stellako* and Birkenhead* (DU 16, 21, 7, 12) show some instances of being Likely to reach Recovery Target #1, only Quesnel and Stellako* do so at more realistic combinations of 10% or higher ERs and decreased productivity. Both Quesnel and Stellako spawn above the Big Bar landslide.

Preliminary results are presented for Quesnel and Stellako* DUs, but no allowable harm statement can be made at this time. (DU 16, 7)

However, as Quesnel was the only EN/TH DU to show a reasonable possibility of reaching Recovery Target #1, below is an example of how several pieces of information could contribute to an allowable harm assessment, once the remaining RPA elements have been assessed and additional information about the Big Bar landslide impacts and mitigation measures are available:

- reasons for COSEWIC designation – "The population faces a number of threats in both freshwater and marine areas, which are causing habitat quality to decline. A potential new threat to the population is the failure of a mining tailings pond that drained into Quesnel Lake in 2014. The population has declined consistently since 2000." (COSEWIC 2017)

- Recovery Target #1 - Likely to meet Recovery Target #1 at an ER of 10% over a wide range of productivities (-30% to +30%) in the base case scenario. However, in the fishway scenario, with a 20% minimum en-route mortality applied in every year, Quesnel was Likely to meet Recovery Target #1 only in those less realistic combinations of near 0% ER and increasing productivity.
- Recovery Target #2 – Unlikely to Exceptionally Unlikely to reach Recovery Target #2 over the entire range of productivities and ERs modelled. It would be unrealistic to expect that a stock that was designated as Endangered could reach a "recovered" state in three generations. In addition, the upper WSP benchmark associated with Recovery Target #2 (1.3 million) is high relative to the historical spawner time series (average spawners since 1948 was 350,000), and also high in the context that the upper WSP benchmark was exceeded by the generational average spawners in only three years (2002-2004) out of 68.
- productivity - There was a 34% decline in average productivity between the 1998-2001 and 2010-2014 brood year generational averages, though the decline appears to have slowed in pace over the last few generations. The current productivity (2010-2014 average) is 45% below the all years average (Table 9). Productivity has been steadily declining since the mid 1980s (Figure 2 in Appendix 1), and we believe it is reasonable to assume that productivity will continue to decrease or at best, stay at current levels in the near future.
- spawner trajectories – Figure 32 in Appendix 3 shows simulated trajectories for two generations beyond the three generations at which the Recovery Targets were evaluated. There was a downward trend in the median spawner abundance at current productivity and 25% ER, which was the maximum ER to result in reaching Recovery Target #1. However, population trajectories were calculated with geometric means which gives more weight to the increasing off-cycle abundances. This ER results in 69% of the trajectories reaching Recovery Target #1 at the end of 12 years. Given the expectations of continued decrease in productivity, and the longer term goal of having the stock reach Recovery Target #2, 25% ER would fall outside the range of "allowable" harm.
- S_{gen} - Comparisons of effective spawners to S_{gen} (Table 10) shows that the last generation of spawners in the Quesnel system is concerningly close to the S_{gen} value (127% of S_{gen}). S_{gen} is the value that divides Red from Amber for the WSP abundance metric. Combined with the productivity assessment, this suggests that a cautious approach should be taken when identifying allowable harm, especially considering that the S_{gen} were measured in total effective spawners.
- threats and limiting factors – To be assessed in companion RPA paper. Recent acute impacts include the: Mount Polley mine embankment breach in 2014 and the Big Bar landslide in the autumn of 2018.

In general, the reasons for the COSEWIC designation given to Quesnel still stand. There has been some improvement in the population decline metric. The COSEWIC report used effective female spawner (EFS) numbers up to 2013 and at that time, the generational average had hovered around 60,000 EFS for half a decade. After 2013, the average generational EFS has stayed over 100,000 EFS (including 2018 return but excluding 2019). Out of the above list, the productivity and S_{gen} considerations stand out as being of the most concern, with the impacts of the Big Bar landslide being a key unknown.

Once some of the immediate Big Bar unknowns and uncertainties are addressed (e.g., incorporation of 2019 en-route mortality and a mitigation plan for the Big Bar site), a preliminary allowable harm assessment for Quesnel could occur. Due to the unknown longer term consequences of the Big Bar landslide, continuing decline in productivity and nearness of the current spawner average to S_{gen}, we recommend that if an allowable harm amount for Quesnel is identified, the allowable harm value should be reviewed annually. Such reviews should continue until the DU improves in status or some of the variability and uncertainty surrounding the assessment inputs and Big Bar impacts are substantively reduced.

8.1.2. Weaver, Portage, Late Stuart, Upper Barriere, Raft*, and Birkenhead* (DU 10, 11, 12, 17, 21, 14)

Weaver, Portage, Late Stuart, Upper Barriere, Raft*, and Birkenhead* were all As Likely As Not to reach Recovery Target #1 at current productivity levels and low mortality rates. Late Stuart is the only DU in this group that spawns upstream of the Big Bar landslide.

Having been designated Special Concern by COSEWIC in 2017, an As Likely as Not to reach Recovery Target #1 could be considered a downgrade for both Raft* and Birkenhead*. The future of the Birkenhead* DU is of particular concern, given its productivity has declined since the late 1980s at one of the steepest rates among Fraser DUs.

Within this group, Upper Barriere, Portage, and Raft* appear more sensitive to increased mortality rates, becoming Unlikely to meet Recovery Target #1 at ERs of 20-25% at current productivity. This compares to ERs of 40% for Late Stuart and Birkenhead* and 50% for Weaver.

The percent change in productivity for Upper Barriere from the 1998-2001 brood year (BY) average to the most recent average (2010-2013 BY) was the largest decline (-62%) among all of the DUs examined in this paper, followed closely by Birkenhead* (-59%)(Table 9). These two DUs were also in the top three steepest declining DUs when the two most recent generations were considered (2006-2009 vs 2010-2013 BY). Even at a 0% ER, 75% of the spawner trajectories for Upper Barriere fall below the historical 25th percentile of spawners (Figure 12 in Appendix 3).

Recognizing that activities in support of the survival and recovery of a DU (e.g., stock assessment, research, conservation, or mitigation activities) could potentially cause mortalities (e.g., stock assessment, research, conservation, or mitigation activities), all sources of harm should be reduced to the maximum extent possible for Weaver, Raft*, Birkenhead*, Portage, Late Stuart and Upper Barriere DUs in order to provide the best opportunity for the DUs to meet Recovery Target #1. (DU 10, 11, 12, 17, 21, 14)

8.1.3. Early Stuart and Bowron (DU 20, 2)

Early Stuart and Bowron were Unlikely to Exceptionally Unlikely to reach Not EN/TH at low to no ERs across the full range of productivities modelled. Both of these stocks spawn upstream of the Big Bar landslide. Early Stuart's recent productivity decline of 23% was not high, when compared to some other Fraser Sockeye stocks, but the current 2010-2013 BY average productivity was 63% lower than the all year average productivity (Table 9). This was the third largest decline among Fraser Sockeye stocks.

At a 10% ER and current or increasing productivity, Early Stuart was Very Unlikely to reach Recovery Target #1 (Figure 23 in Appendix 3). If productivity decreases or ER increases, Early Stuart becomes Exceptionally Unlikely to reach Recovery Target #1 in the next 12 years. Of note, over 75% of the spawner abundances in nearly every year simulated for Early Stuart was less than the historical 25th quartile of four year average spawner abundances.

Bowron's productivity has been steadily declining since the late 1960s, with a recent decline of 39% and overall decline of 60% from the long-term average (Table 9). Bowron was Unlikely to reach Recovery Target #1 even at ERs below 10% and increasing productivity (Figure 28 in Appendix 3).

Recognizing that activities in support of the survival and recovery of a DU (e.g., stock assessment, research, conservation, or mitigation activities) could potentially cause mortalities, all sources of harm should be reduced to the maximum extent possible for Early Stuart and Bowron DUs in order to provide the *best opportunity for the survival* of these DUs. (DU 20, 2)

8.1.4. Taseko and Widgeon (DU 22, 24)

Unlike the other Fraser Sockeye DUs in this paper, only estimates of spawner numbers were available for Widgeon and Taseko. Taseko escapement estimates in particular, are highly uncertain due to Taseko fish spawning in a glacial system. Both stocks are small and highly variable. Due to the constrained size of its spawning location, Widgeon will likely never be a large stock. Exploitation rates taken from proxy stocks and SMUs (Figure 20 – Widgeon, Figure 41 – Taseko) do not appear to be correlated with estimated spawning escapement numbers.

For Taseko and Widgeon, the amount of uncertainty does not allow us to recommend a level of allowable harm using the methods described in this paper. However, using the other small stocks assessed in this report as proxies, all sources of harm should be reduced to the maximum extent possible for Taseko and Widgeon. (DU 22, 24)

9. ACKNOWLEDGMENTS

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- The subject matter experts: Keri Benner, Pete Nicklin, Catarina Wor, Paul Grant, Michael Arbeider
- The sharers of R-code: Catherine Michielsens, Brendan Connor

and all of the participants on our every-other Monday check-in calls over the past seven months.

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11. APPENDIX 1: STOCK-RECRUIT MODELS (ELEMENT 13 - PT 1)

Previous Fraser Sockeye multi-year forward simulations focused on near-equilibrium conditions, estimated 48 years into the future (Pestal et al. 2011). It used a standard Larkin stock-recruit model fitted to all years of data, based on advice from an expert workshop (DFO 2006).

Preliminary simulations for this project showed that the 12 year forward trajectories based on these parameter estimates were implausibly optimistic for stocks of concerns with recent abundances well below the historical range. This was due to a combination of 1. the structure of the Larkin model, which includes density-dependent lag terms (beta 1, 2, 3); 2. a higher intrinsic productivity (alpha), which has a pronounced effect at lower spawner numbers; and 3. the lower spawner numbers that the at-risk stocks were currently at.

To identify more appropriate SR models for the RPA analyses, we convened a group of experts, identified 8 candidate model variations, used a preliminary evaluation of model fits to identify a shortlist of 5 candidate models, then completed a formal model ranking test, and selected 1-2 SR models for each stock to be used for the RPA simulations. Sections 5.3.1,5.3.3, and 5.3.4 describe the model selection approach. This appendix documents the model ranking results and describes the stock-specific rationale for the final model selection.

11.1. ALTERNATIVE SR MODELS

Both the Ricker and Larkin forms of SR models (Pestal et al 2011) were used in this assessment. Based on these forms, eight variations of these models were employed, as described below.

The parameter estimations was conducted in JAGS, running 4 chains, each with a burnin of 15,000, thin of 7 and total iterations of 32,500. 10,000 Markov chain Monte Carlo (MCMC) samples were taken from the posterior distribution. Forward simulations were based on 5000 randomly selected parameter sets (i.e., paired α, β and ε in the case of the Ricker-based models).

11.1.1. Ricker

The Ricker model is commonly used to represent stock-recruit dynamics of Pacific salmon.

$$\ln (R_t/S_{t-4}) = \alpha - \beta_0 S_{t-4} + \varepsilon_t$$

Where R is the recruits in year t, S is the effective female spawners from the brood year t, α is the productivity parameter, α/β0 describes the capacity of the system for the Ricker equation and ε is the annual process error in recruitment.

11.1.2. Ricker – half productivity

Starting with the same 10,000 MCMC samples that came from SR-1, the median α value was divided by two to determine the half productivity value. The forward simulations were then based on 2,500 randomly selected parameter sets (from the original 10,000) with α values that were lower than the half productivity median and 2,500 sets with α values that were higher.

11.1.3. Ricker – recent productivity - recursive

A Bayesian formulation of Peterman et al (2003)'s Kalman filter model was obtained from Catherine Michielsens (Pacific Salmon Commission). This recursive Ricker model includes a time-varying alpha parameter which acts as a proxy for historical patterns of productivity.

The observation error and process error in the original Bayesian code was combined into a single term for the purpose of simplifying the model and in anticipation of further changing it to work with the Larkin stock-recruit model.

An informative prior for alpha was taken from the stock-specific alpha (median and standard deviation) estimated by the non-recursive Bayesian Ricker model. The beta prior was as described in Pestal et al (2012), that is, as a lognormal with a mean of the largest observed abundance and an upper bound of three times the largest observed.

To represent the current productivity of each stock, in each of the last 4 years estimated by the recursive model, 10,000 MCMC sample sets each containing an alpha, beta and a variance term were sampled from the posterior distribution. These 40,000 sample sets were then sub-sampled and combined in order to model-average the results for use in the forward simulation models.

11.1.4. Ricker (DNA years)

These model runs used the same method as SR-1 (Ricker), but the parameters were fit to years in the SR dataset when stock identification was based on DNA methods (i.e., beginning in brood year 2002).

11.1.5. Ricker (5 generations)

These model runs used the same method as SR-1 (Ricker), but the SR dataset was restricted to the last 20 brood years of stock-recruit data, which is equivalent to 5 generations of age 4 Sockeye. This was consistent with the number of generations used in the Interior Fraser Coho RPA (Arbeider et al, 2020).

11.1.6. Larkin

The Larkin model is used to approximate the cyclic patterns observed in some Fraser River Sockeye stocks.

$$\ln (R_t/S_{t-4}) = \alpha - \beta_0 S_{t-4} - \beta_1 S_{t-5} - \beta_2 S_{t-6} - \beta_3 S_{t-7} + \varepsilon_t$$

Where R is the recruits in year t, S is the effective female spawners from the brood year t, α is the productivity parameter, α/β0 describes the capacity of the system for the Ricker equation, β1, β2 and β3 are the Larkin parameters that describe the between-cycle delayed-density interaction, and ε is the annual process error in recruitment.

Other than the use of a Larkin rather than a Ricker SR form, the modelling process described for SR-1(Ricker) was used.

11.1.7. Larkin - half productivity

The modelling process was similar to that used for SR-2 (Ricker – half productivity), except the MCMC samples were drawn from the Larkin model.

11.1.8. Larkin - recent productivity - recursive

These model runs used the same method as SR-3 (Ricker – recent productivity), except using the Larkin stock-recruit model form.

recursive model fit test / checks: - observation error + process error vs combined error term (Ricker version only) - checked distribution of the variances – that they were not asymmetrically distributed - informative vs uninformative alpha (Ricker version only) - checked that pattern of alphas was not greatly influenced by the addition of an informative alpha - recursive alpha patterns using Ricker vs Larkin SR model - checked that pattern of alphas was not entirely different due to choice of SR model form

11.2. RECENT PRODUCTIVITY

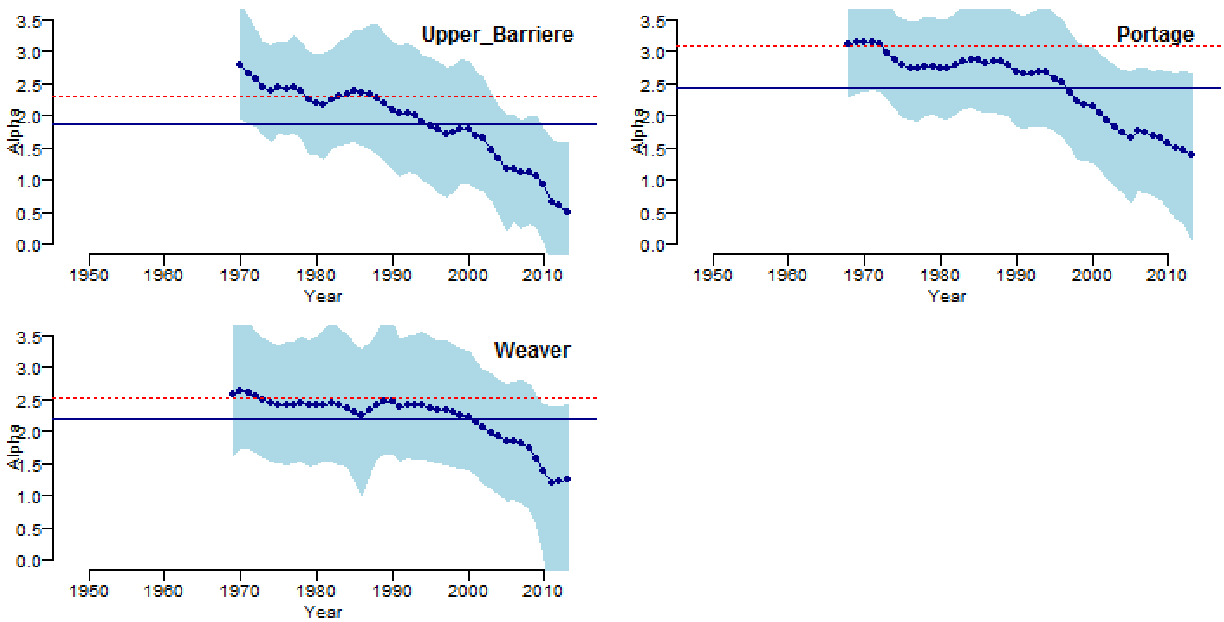

Figure 1. Productivity patterns - Endangered / Threatened DUs not affected by Big Bar slide (Element 13, part 1). Blue points show the medians of annual estimates of the time-varying Larkin (LRB) alpha parameter. Solid blue line is the average of all of the time vary alpha medians. Dotted red line is the median alpha estimate from the regular Larkin (LA) model. Light blue shading shows the 95% probability intervals.

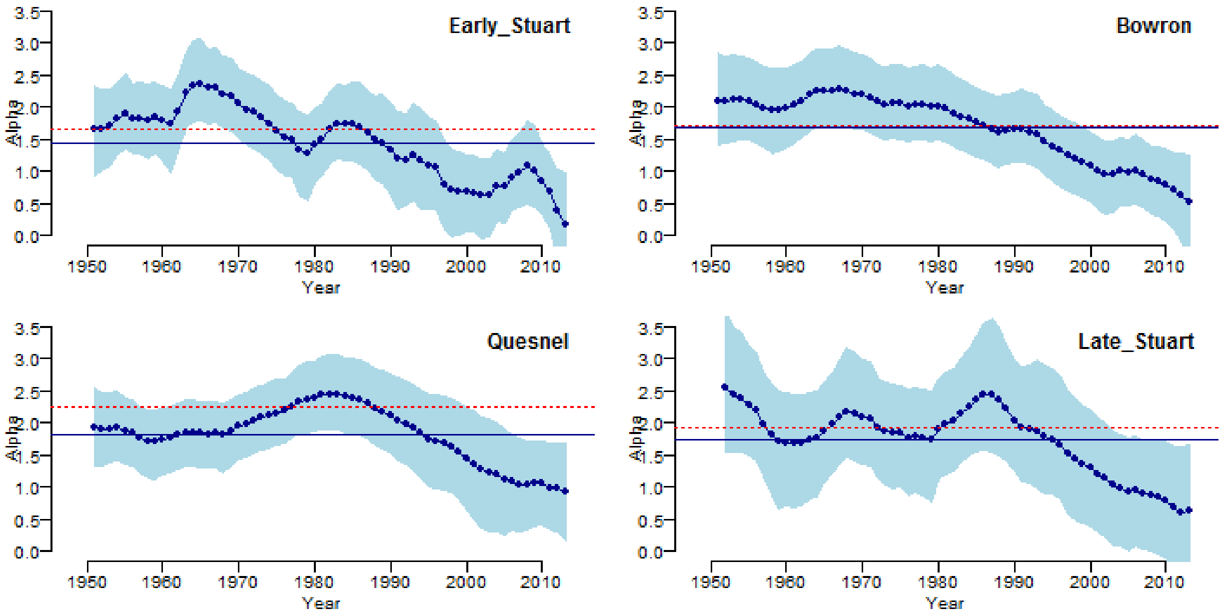

Figure 2. Productivity patterns - Endangered / Threatened DUs affected by Big Bar slide (Element 13, part 1). Blue points show the medians of annual estimates of the time-varying Larkin (LRB) alpha parameter. Solid blue line is the average of all of the time vary alpha medians. Dotted red line is the median alpha estimate from the regular Larkin (LA) model. Light blue shading shows the 95% probability intervals.

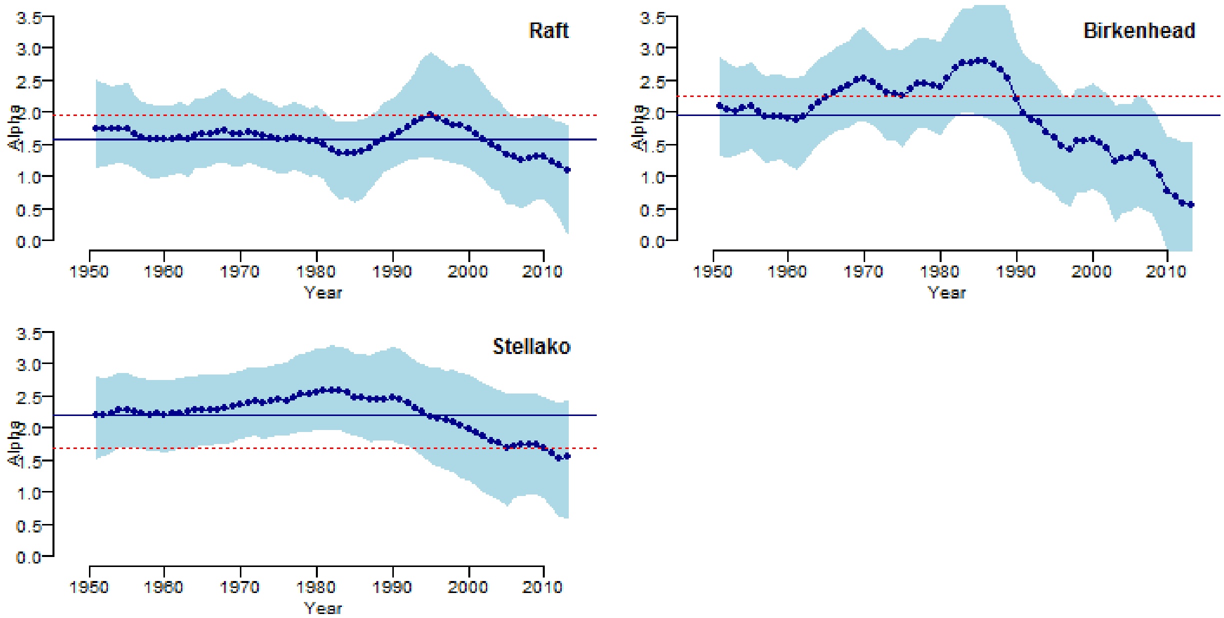

Figure 3. Productivity patterns - Special Concern DUs. (Element 13, part 1). Blue points show the medians of annual estimates of the time-varying Larkin (LRB) alpha parameter. Solid blue line is the average of all of the time vary alpha medians. Dotted red line is the median alpha estimate from the regular Larkin (LA) model. Light blue shading shows the 95% probability intervals. Stellako (DU7) is affected by Big Bar slide.*

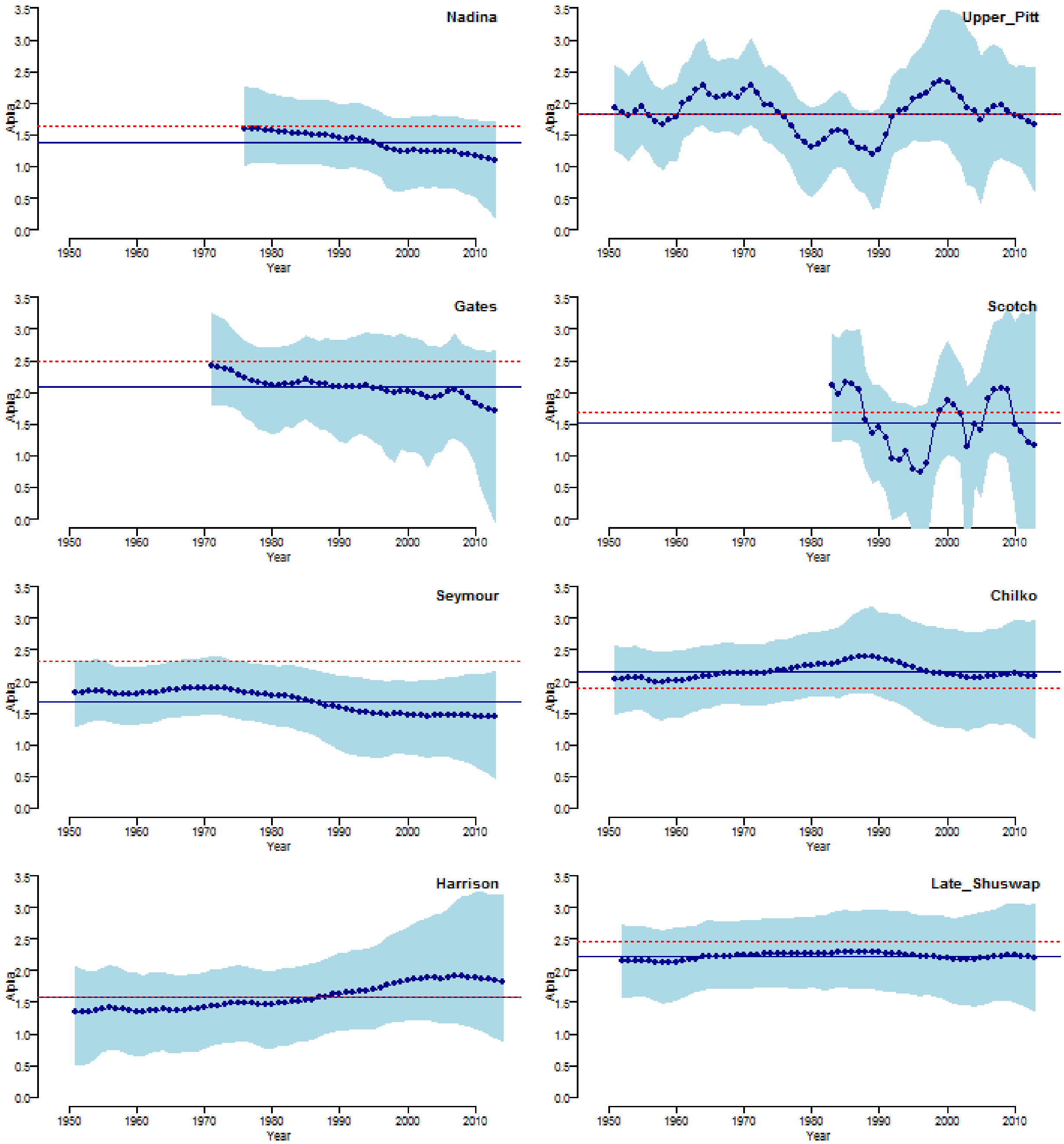

Figure 4. Productivity patterns - Not At Risk DUs. (Element 13, part 1). Blue points show the medians of annual estimates of the time-varying Larkin (LRB) alpha parameter. Solid blue line is the average of all of the time vary alpha medians. Dotted red line is the median alpha estimate from the regular Larkin (LA) model. Light blue shading shows the 95% probability intervals. Nadina and Chilko are affected by Big Bar slide.

11.3. PATTERN IN SR MODEL RANKS

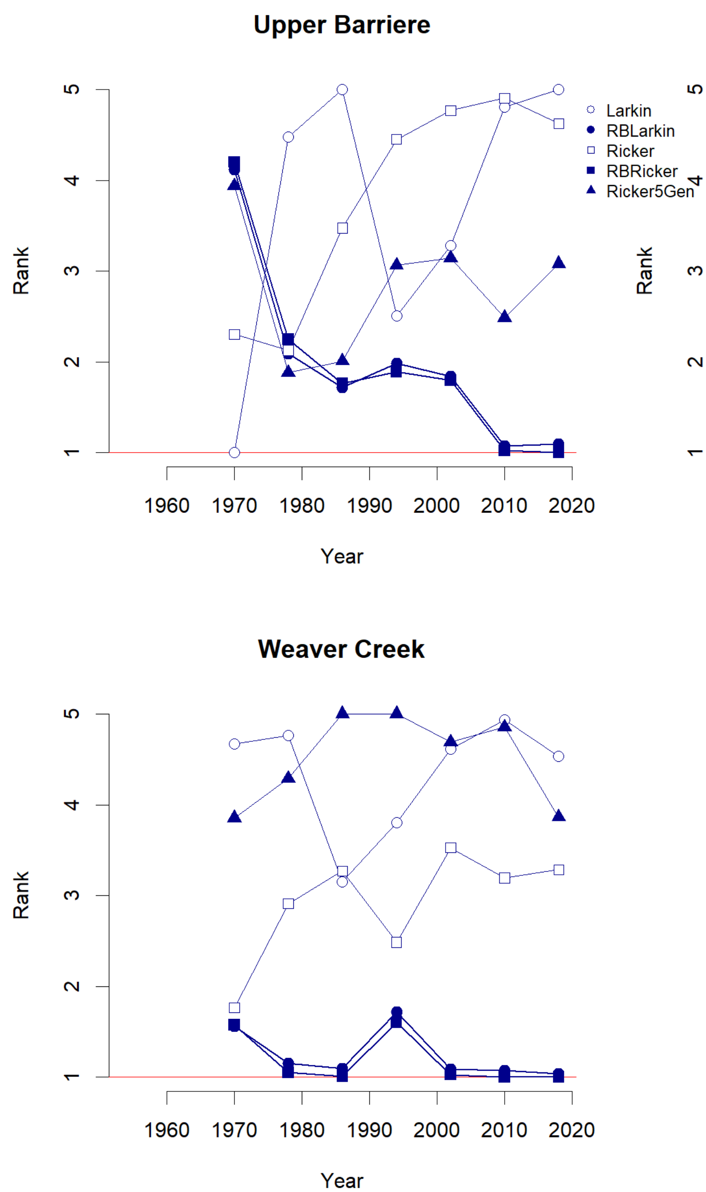

Figure 5. Retrospective Pattern of SR Model Ranks - Endangered / Threatened DUs not affected by Big Bar slide (Element 13, part 1). Each line shows the pattern of scaled average ranks (section 5.3.1) for one SR model over time, with each point marking the end year of a 2-generation (8yr) time window. The final point covers 2011-2018, but observed recruits were available only for 2011-2013 brood years (i.e., up to 2018 return) at this time. SR models that capture recent productivity are shown with full symbols. SR models using all-year average productivity are shown with empty symbols.

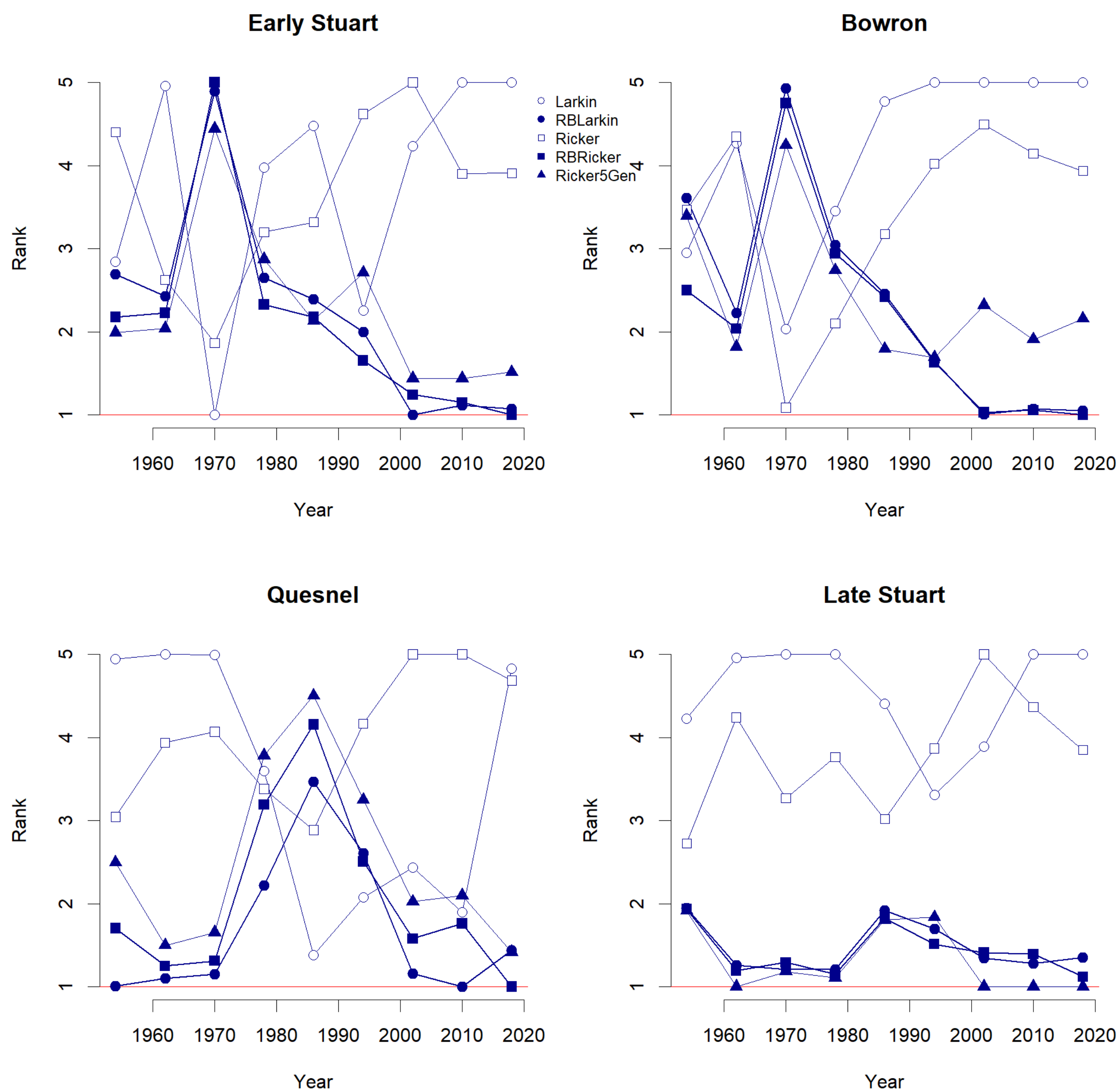

Figure 6. Retrospective Pattern of SR Model Ranks - Endangered / Threatened DUs affected by Big Bar slide (Element 13, part 1). Each line shows the pattern of scaled average ranks (section 5.3.1) for one SR model over time, with each point marking the end year of a 2-generation (8yr) time window. The final point covers 2011-2018, but observed recruits were available only for 2011-2013 brood years (i.e., up to 2018 return) at this time. SR models that capture recent productivity are shown with full symbols. SR models using all-year average productivity are shown with empty symbols.

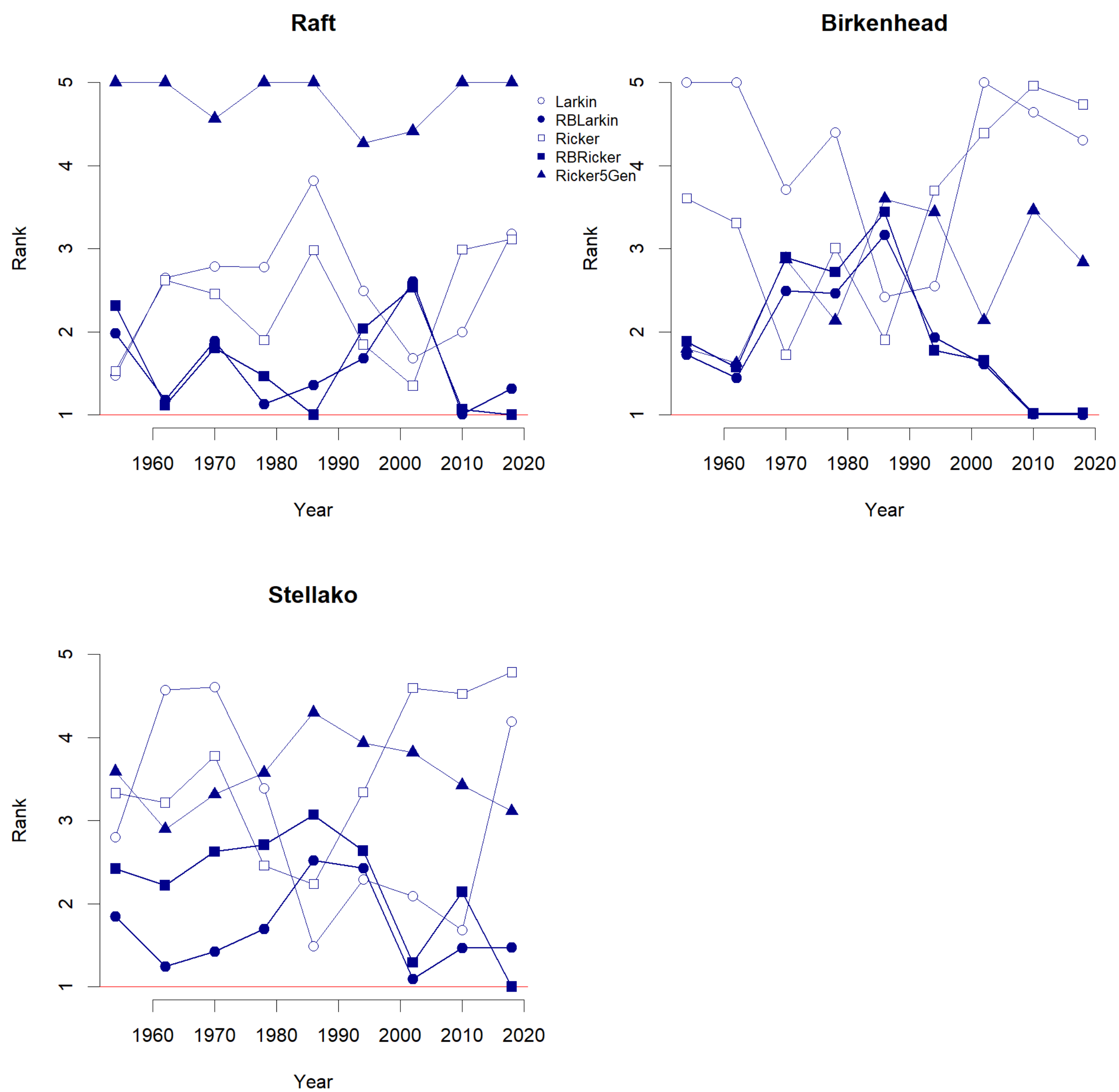

Figure 7. Retrospective Pattern of SR Model Ranks - Special Concern DUs (Element 13, part 1). Each line shows the pattern of scaled average ranks (section 5.3.1) for one SR model over time, with each point marking the end year of a 2-generation (8yr) time window. The final point covers 2011-2018, but observed recruits were available only for 2011-2013 brood years (i.e., up to 2018 return) at this time. SR models that capture recent productivity are shown with full symbols. SR models using all-year average productivity are shown with empty symbols.

11.4. MOST RECENT SR MODEL RANKS

Upper Barriere

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	5	5	5	5	5	5
LRB	1.08	1.08	1.08	1.08	1.14	1.09
R5Gen	2.62	2.62	2.63	2.63	4.89	3.08
RA	4.83	4.81	4.87	4.86	3.75	4.62
RRB	1	1	1	1	1	1

Portage

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	1	1	1.02	1.02	1.08	1.02
LRB	1.1	1.11	1	1	1	1.04
R5Gen	3.64	3.66	3.91	3.91	5	4.02
RA	5	5	5	5	4.01	4.8
RRB	1.52	1.54	2.13	2.14	1.83	1.83

Weaver Creek

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	5	5	5	5	2.67	4.53
LRB	1.05	1.05	1.01	1.01	1.05	1.04
R5Gen	4.08	4.12	3.06	3.06	5	3.86
RA	3.76	3.73	3.43	3.43	2.07	3.28
RRB	1	1	1	1	1	1

Figure 8. Most Recent SR Model Ranks - Endangered / Threatened DUs not affected by Big Bar slide (Element 13, part 1). Tables shows scaled average ranks (section 5.3.1) for recruits from brood years 2011-2013, based on comparing estimate recruits from 5000 MCMC parameter sample to observed recruits.

Early Stuart

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	5	5	5	5	5	5
LRB	1.07	1.07	1.07	1.07	1.08	1.07
R5Gen	1.43	1.43	1.48	1.45	1.77	1.51
RA	3.89	3.88	3.9	3.88	3.98	3.91
RRB	1	1	1	1	1	1

Bowron

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	5	5	5	5	5	5
LRB	1.03	1.06	1.06	1.06	1.02	1.05
R5Gen	1.91	1.97	2	2.01	2.91	2.16
RA	4.06	4.06	4.07	4.05	3.43	3.94
RRB	1	1	1	1	1	1

Quesnel

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	5	5	5	5	4.15	4.83
LRB	1.49	1.46	1.49	1.44	1.32	1.44
R5Gen	1.23	1.3	1.2	1.3	2.06	1.42
RA	4.63	4.64	4.58	4.6	5	4.69
RRB	1	1	1	1	1	1

Late Stuart

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	5	5	5	5	5	5
LRB	1.27	1.34	1.23	1.27	1.66	1.35
R5Gen	1	1	1	1	1	1
RA	3.9	3.9	3.95	3.95	3.55	3.85
RRB	1.07	1.15	1.06	1.1	1.22	1.12

Figure 9. Most Recent SR Model Ranks - Endangered / Threatened DUs affected by Big Bar slide (Element 13, part 1). Tables shows scaled average ranks (section 5.3.1) for recruits from brood years 2011-2013, based on comparing estimate recruits from 5000 MCMC parameter sample to observed recruits.

Raft

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	3.58	3.23	3.68	3.52	1.9	3.18
LRB	1.37	1.32	1.38	1.35	1.16	1.32
R5Gen	5	5	5	5	5	5
RA	3.54	3.16	3.55	3.36	1.95	3.11
RRB	1	1	1	1	1	1

Birkenhead

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	4.44	4.42	3.85	3.82	5	4.31
LRB	1	1	1	1	1.01	1
R5Gen	2.83	2.82	2.64	2.63	3.26	2.84
RA	5	5	5	5	3.68	4.74
RRB	1	1	1.05	1.05	1	1.02

Stellako

Model	MRE	MAE	MPE	MAPE	RMSE	Avg
LA	4.01	4.03	4.69	4.71	3.49	4.19
LRB	1.32	1.38	1.62	1.65	1.39	1.48
R5Gen	2.57	2.71	2.59	2.69	5	3.11
RA	5	5	5	5	3.93	4.79
RRB	1	1	1	1	1	1

Figure 10. Most Recent SR Model Ranks - Special Concern DUs (Element 13, part 1). Tables shows scaled average ranks (section 5.3.1) for recruits from brood years 2011-2013, based on comparing estimate recruits from 5000 MCMC parameter sample to observed recruits.

12. APPENDIX 2: RPA MODEL (ELEMENT 13 - PT 2)

12.1. GENERAL STRUCTURE

The simulation model built for this assessment (the *RPA model*) has a different purpose from the model used for in recent year to test alternative harvest control rules (the *FRSSI model*), as described in Section 5.3.

The RPA model was designed with the following objectives:

- fast forward simulation of many trajectories
- focus on next 3-4 generations
- focus on starting conditions
- focus on each DU's individual response to different levels of exploitation rate

In contrast, the FRSSI model (Pestal et al. 2011) was designed to evaluate the long-term performance (12 generations) of various harvest rules, including harvest allocation and in-season management constraints.

Based on these objectives, the RPA model has the following structure:

- simulate each individual stock independently (but run all stocks as a batch)
- calculate recruits for a brood year using, then apply a fixed age proportion to calculate run size
- apply fixed exploitation rate and a randomly sampled en-route mortality to calculate spawners
- repeat this sequence for 20 years
- repeat this 20yr simulation 5000 times (each with a different sample of the SR parameters)

12.2. SPECIFIC CALCULATIONS

For each stock, the calculations were:

$$\begin{aligned}
Rec_y &= fn(Spn_y, Pars) \\
Rec_{y-1} &= fn(Spn_{y-1}, Pars) \\
Run_{y+4} &= Rec_y * p_4 + Rec_{y-1} * (1 - p_4) \\
Spn_{y+4} &= Run_{y+4} * (1 - ER) * (1 - ERM)
\end{aligned}$$

where

y = year
Spn = total abundance of spawners
Rec = total recruits produced from these spawners
Run = total abundance of returning adults (from multiple brood years)
Pars = SR parameters as per Section 1.1
ER = exploitation rate
ERM = en-route mortality
p_4 = proportion of age 4 fish

Section 4.5 documents the overall forward simulation code, and the functions that implement array versions of Eq 1 and 2.

13. APPENDIX 3: SIMULATION RESULTS

DUs were organized in this section as follows:

Endangered & Threatened - not affected by Big Bar landslide

- Upper Barriere/Fennell (North Barriere-ES DU14)
- Portage (Seton-L DU17)
- Weaver (Harrison (U/S)-L DU10)
- Widgeon (Widgeon(River-Type) DU24)

Endangered & Threatened - affected by Big Bar Landslide

- Early Stuart (Takla-Trembleur-EStu DU20)
- Bowron (Bowron-ES DU2)
- Quesnel (Quesnel-S DU16)
- Late Stuart (Takla-Trembleur-Stuart-S DU21)
- Taseko (Taseko-ES DU 22)

Special Concern

- Raft* (Kamloops-ES DU11)
- Birkenhead* - (Lillooet-Harrison-L DU12)
- Stellako* (Francois-Fraser-S DU7)

Note: of the special concern DUs, Stellako* is the only one affected by Big Bar landslide.

13.1. ENDANGERED & THREATENED - NOT AFFECTED BY BIG BAR LANDSLIDE

13.1.1. Upper Barriere/Fennell (North Barriere-ES DU14)

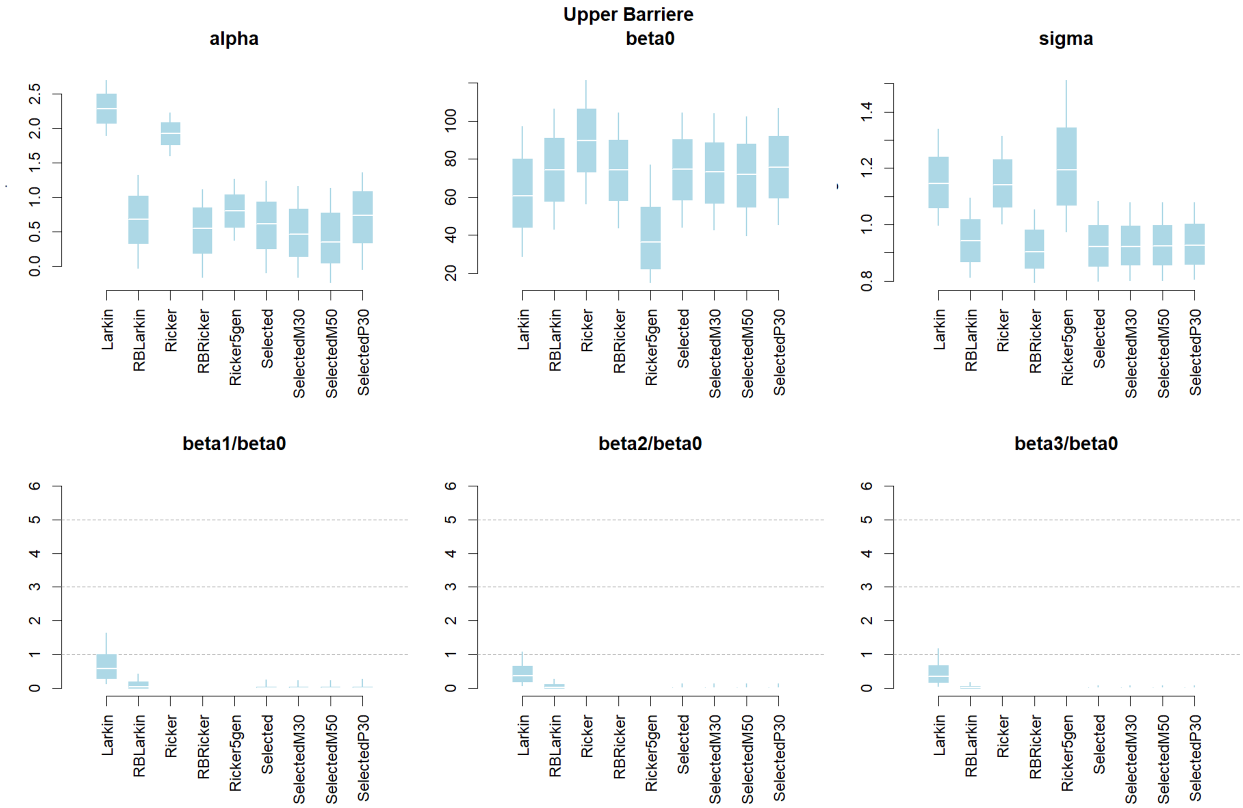

Figure 11. Posterior Distributions for Alternative SR model Parameters - Upper Barriere (DU14) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

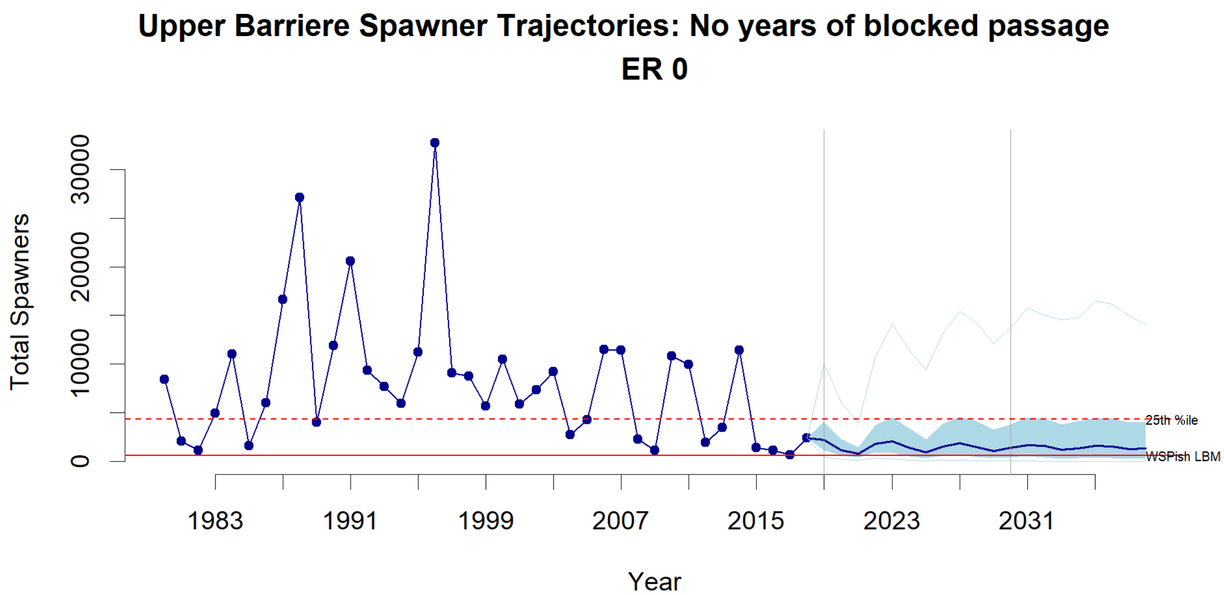

Figure 12. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions - Upper Barriere (DU14) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

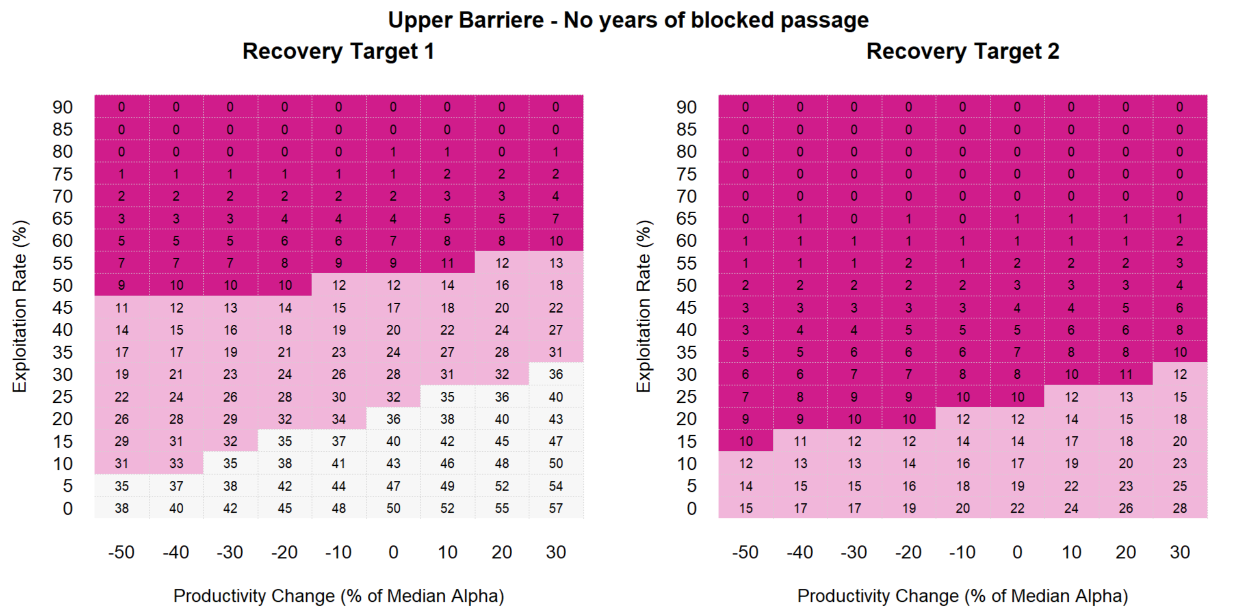

Figure 13. Effect of varying exploitation rate across alternative productivity scenarios - Upper Barriere (DU14) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

13.1.2. Portage (Seton-L DU17)

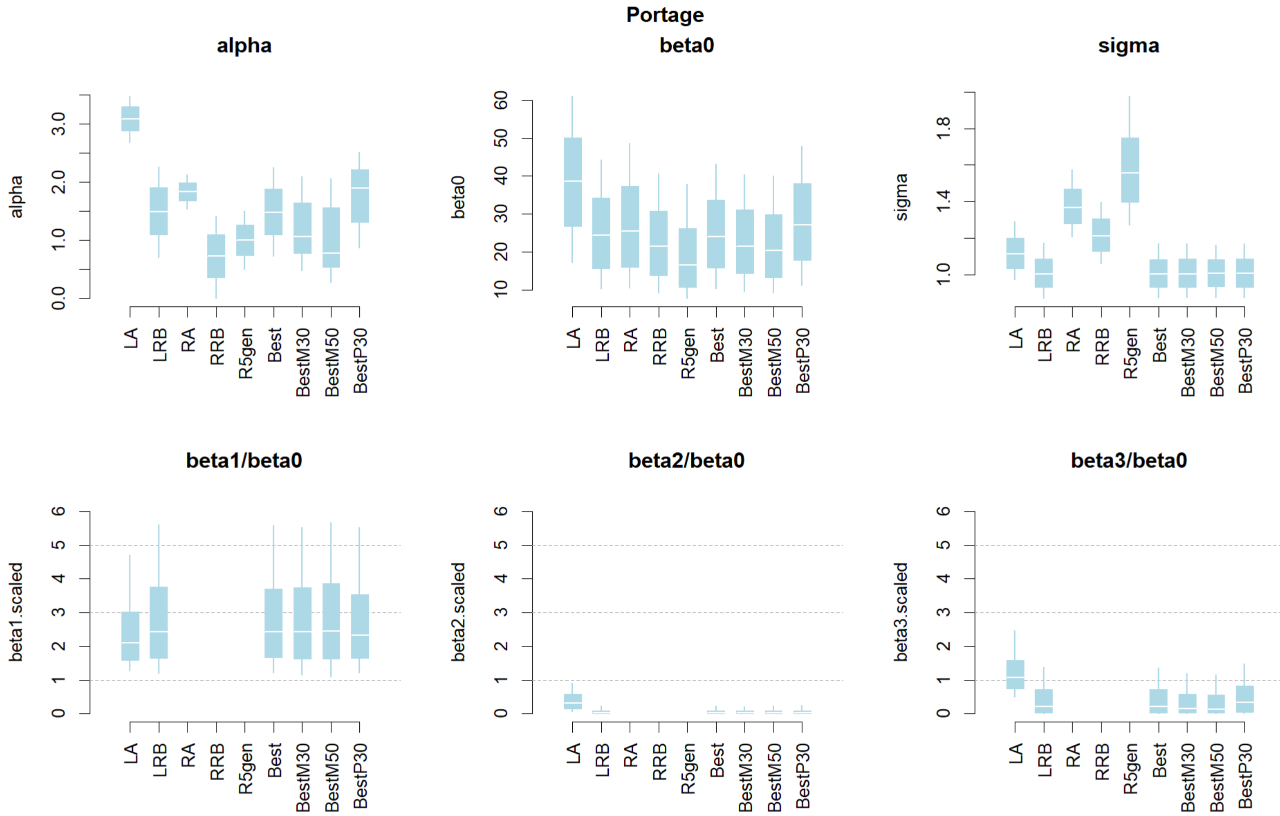

Figure 14. Posterior Distributions for Alternative SR model Parameters – Portage (DU17) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

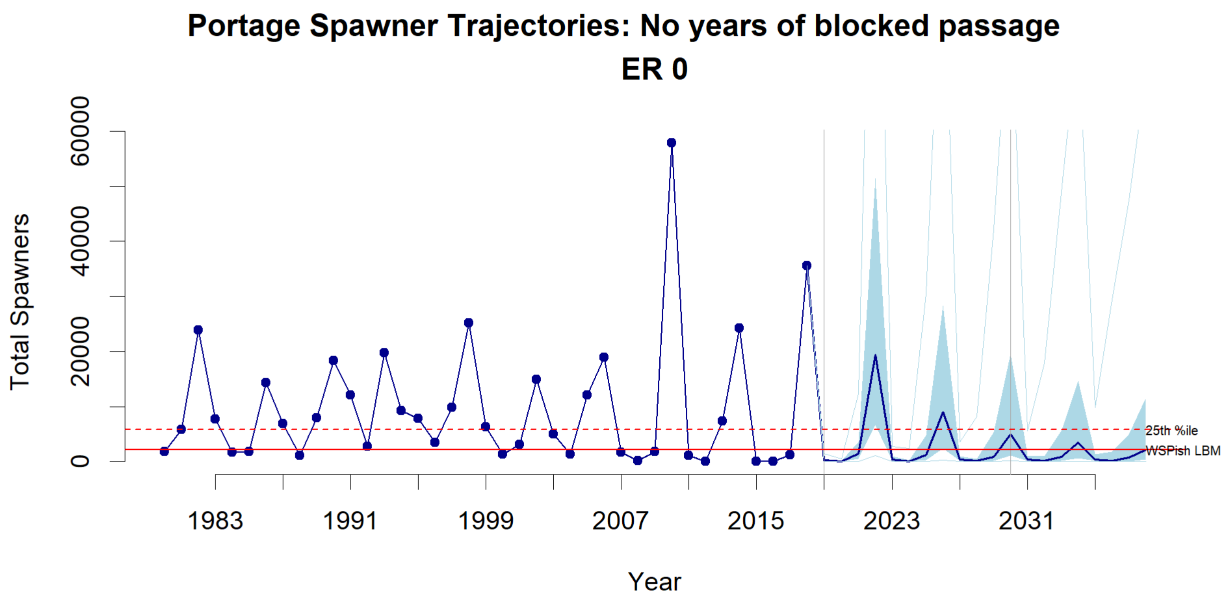

Figure 15. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions – Portage (DU17) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

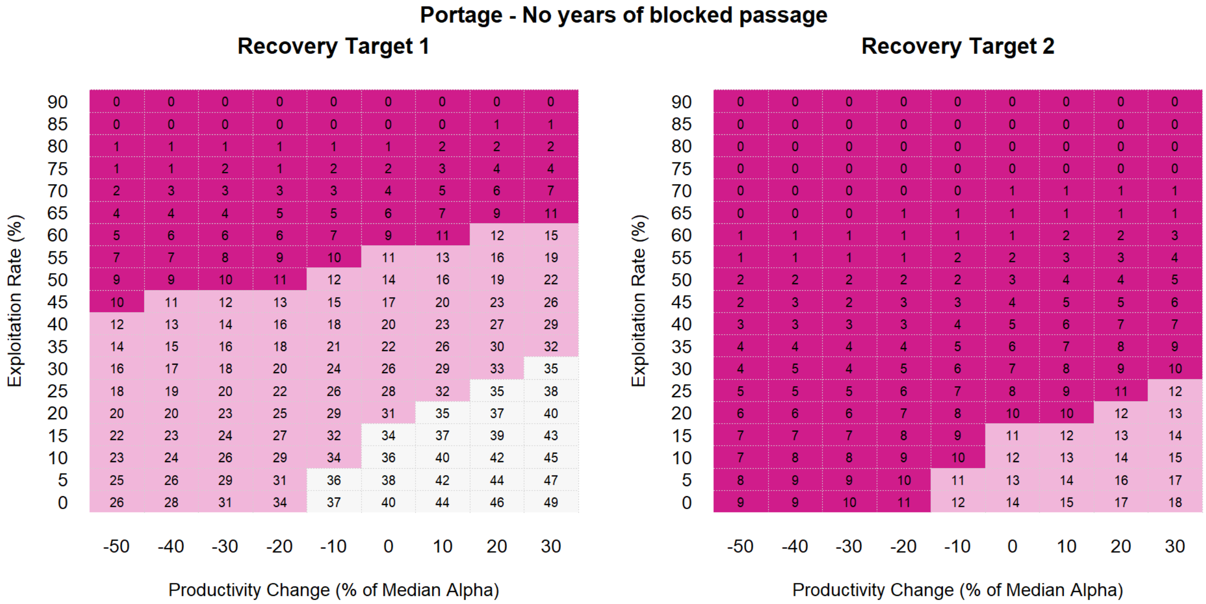

Figure 16. Effect of varying exploitation rate across alternative productivity scenarios – Portage (DU17) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

13.1.3. Weaver (Harrison (U/S)-L DU10)

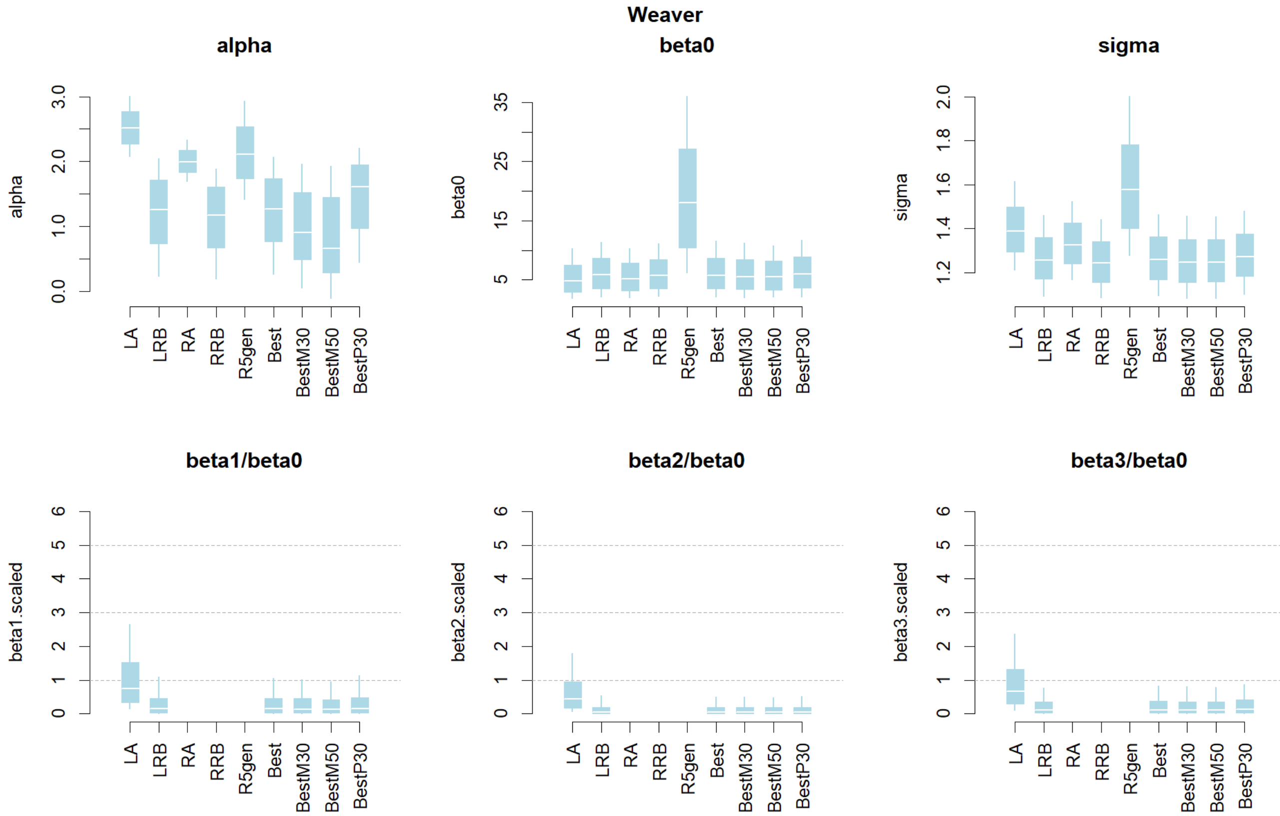

Figure 17. Posterior Distributions for Alternative SR model Parameters - Weaver (DU 10) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

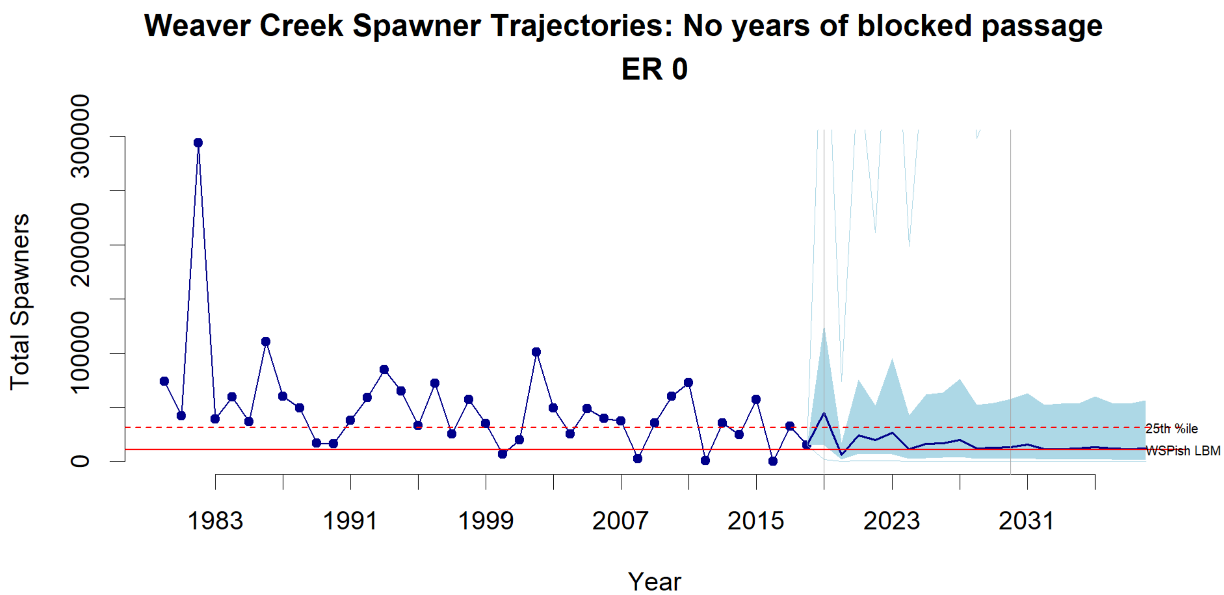

Figure 18. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions – Weaver (DU 10) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

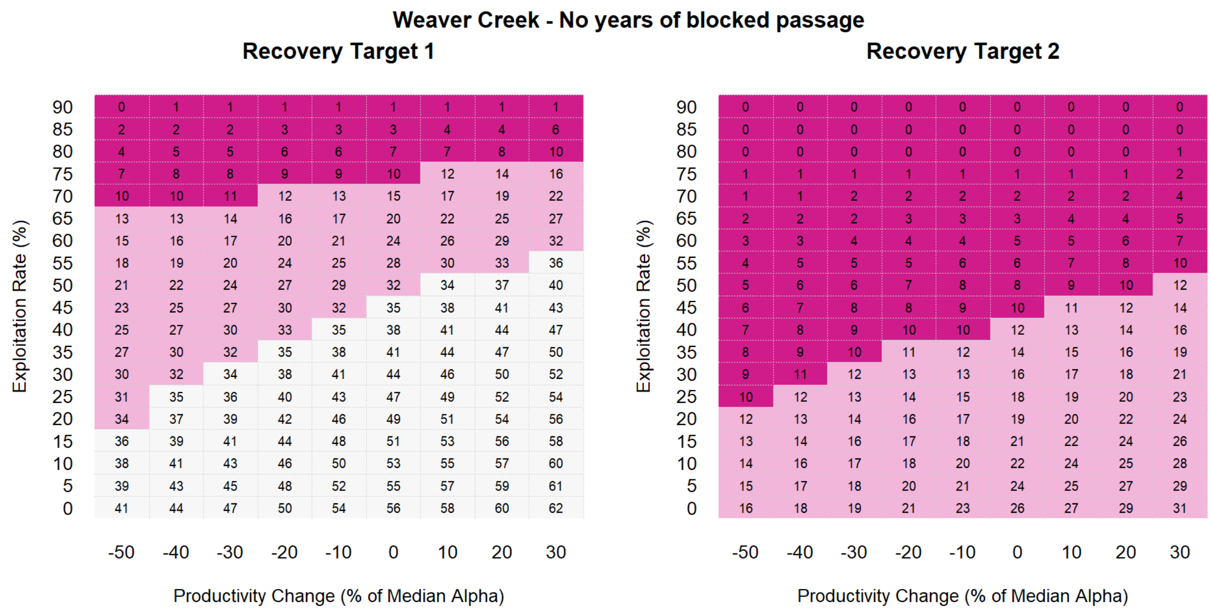

Figure 19. Effect of varying exploitation rate across alternative productivity scenarios – Weaver (DU 10) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

1.1.1 Widgeon (Widgeon (River-Type) DU24)

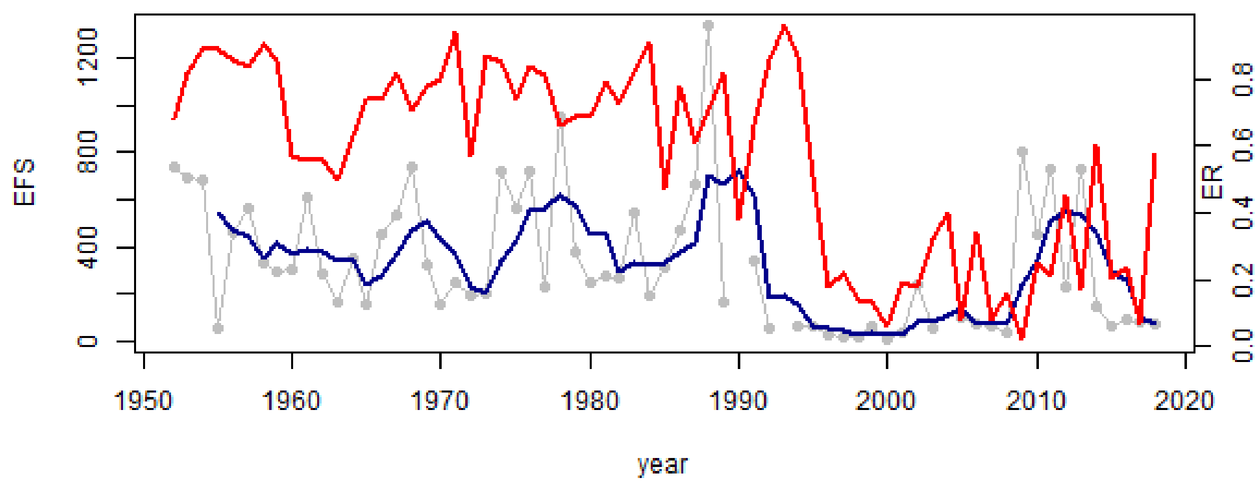

Figure 20. Time Series of Effective Female Spawners (annual in gray, 1 generation running average in blue solid line) and Exploitation Rate (red line) - Widgeon (DU24) (Element 2).

13.2. ENDANGERED & THREATENED - AFFECTED BY BIG BAR LANDSLIDE

13.2.1. Early Stuart (Takla-Trembleur-EStu DU20)

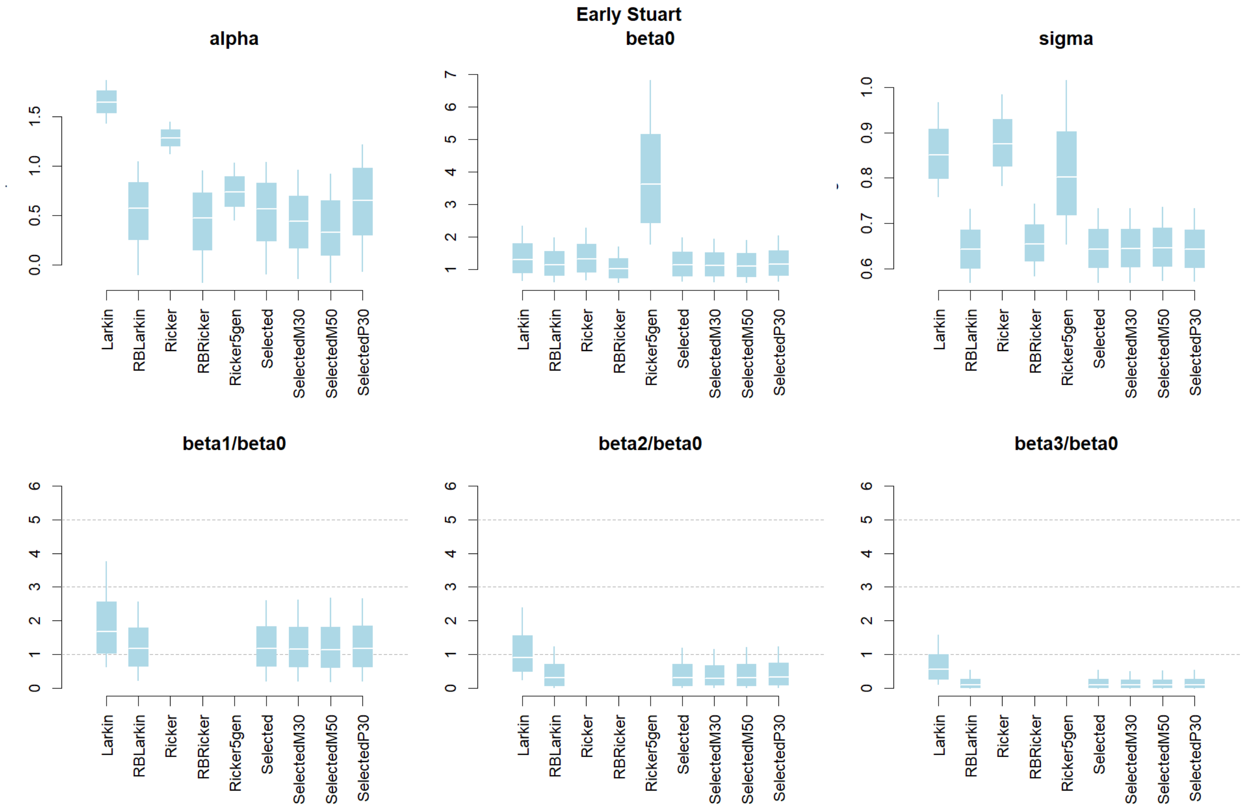

Figure 21. Posterior Distributions for Alternative SR model Parameters - Early Stuart (DU20) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

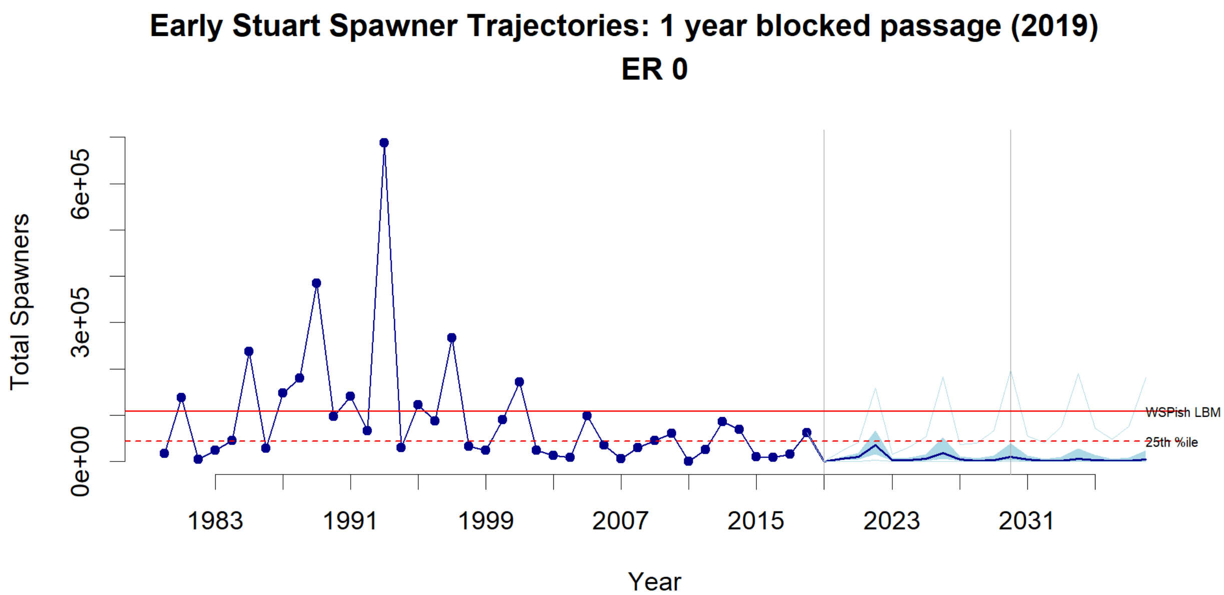

Figure 22. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions - Early Stuart (DU20) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

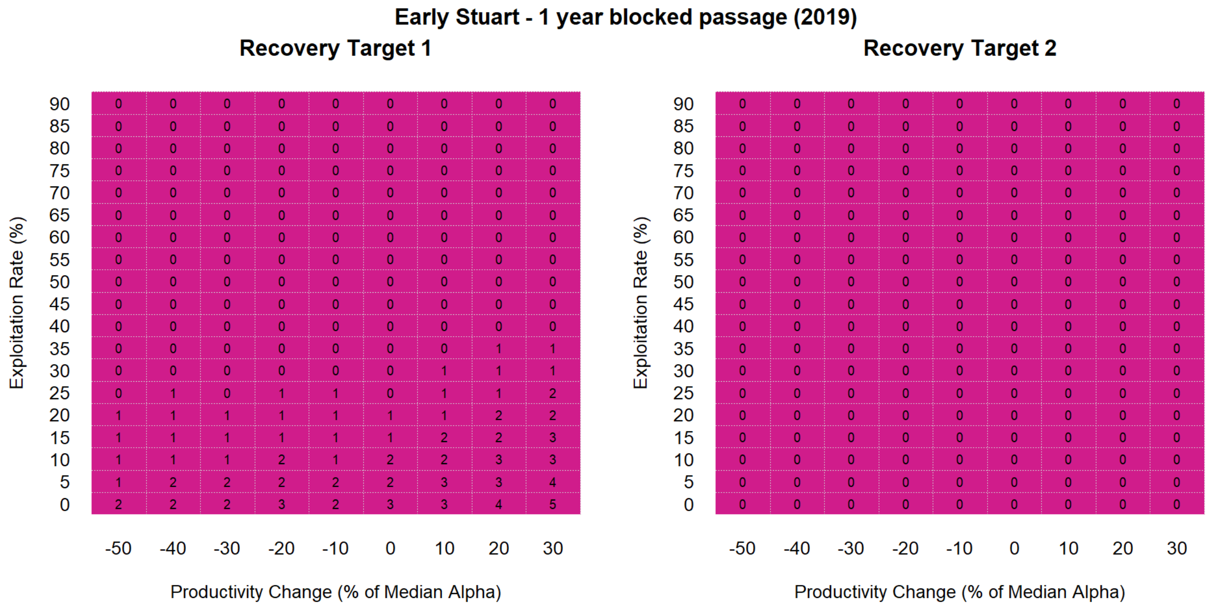

Figure 23. Effect of varying exploitation rate across alternative productivity scenarios - Early Stuart (DU20) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

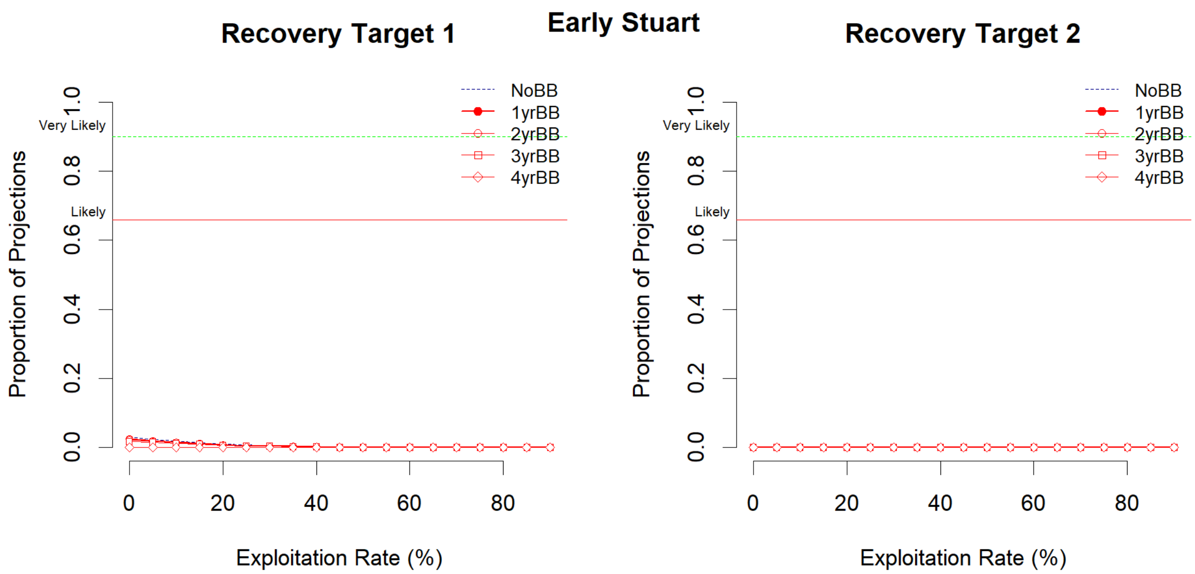

Figure 24. Effect of varying exploitation rate under alternative Big Bar impact scenarios - Early Stuart (DU20) (Element 20). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate for one of the Big Bar landslide scenarios described in section 6.1.3, where 1yrBB = 99.5% mortality applied to 2019 return year, 2yrBB = 99.5% mortality applied to 2019 and 2020 return years, etc. The thick red line with solid points in this plot corresponds to the "0" productivity change column in the grids shown in the previous plot. The horizontal lines mark the IPCC probability levels for Likely in solid red and Very Likely in dashed green (Table 7).

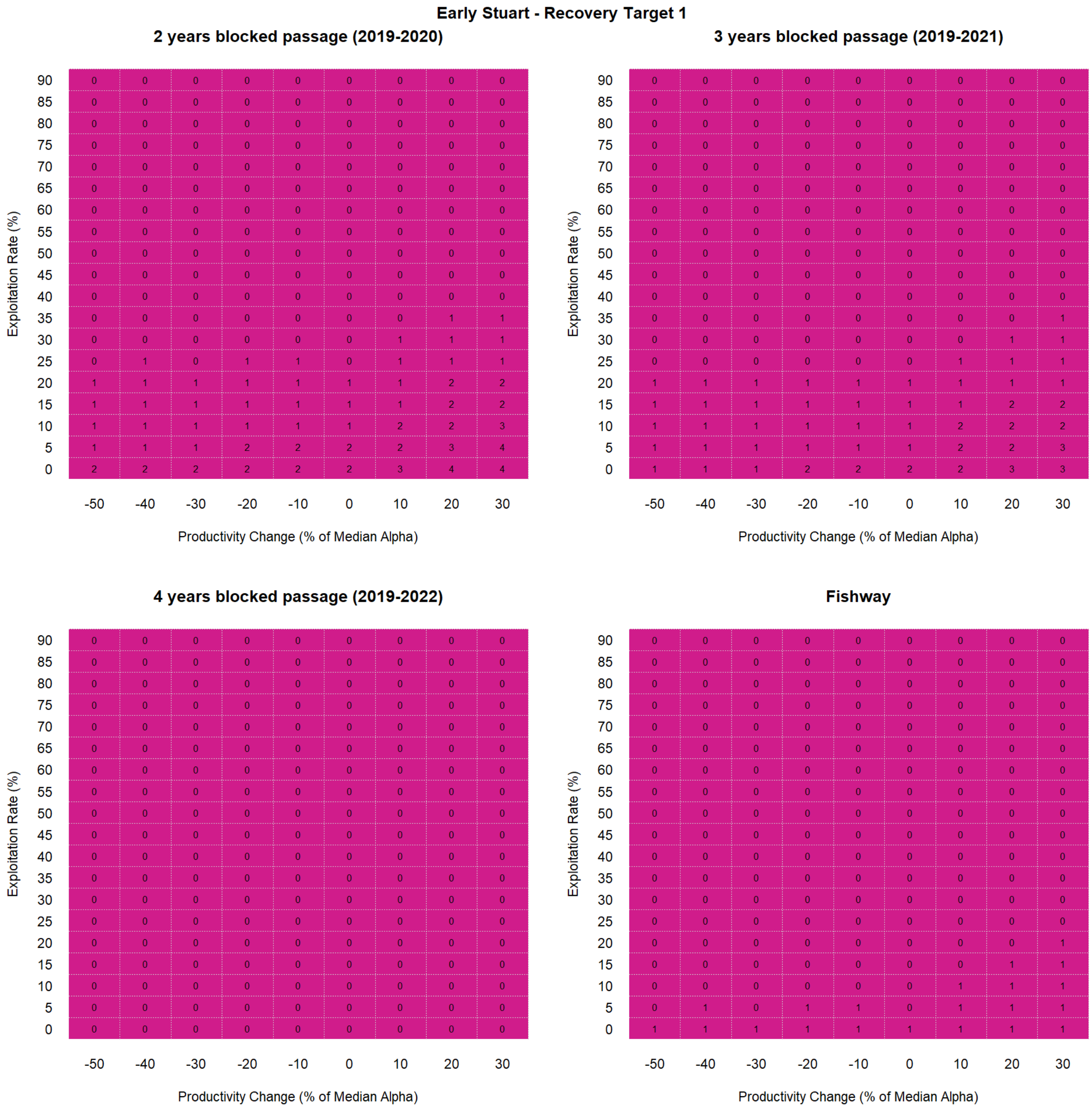

Figure 25. Effect of varying exploitation rate across alternative productivity scenarios in combination with alternative Big Bar impact scenarios - Early Stuart (DU20) (Element 20). Each panel shows simulated performance relative to Recovery Target #1 (section 5.2) under one of the alternative Big Bar landslide scenarios. Panel layout is the same as the earlier figure. The blocked passage panels each show the effect of 99.5% en-route mortality in the years specified from Big Bar impacts, and the fishway panel scenario was described in section 6.1.3.

13.2.2. Bowron (Bowron – ES DU2)

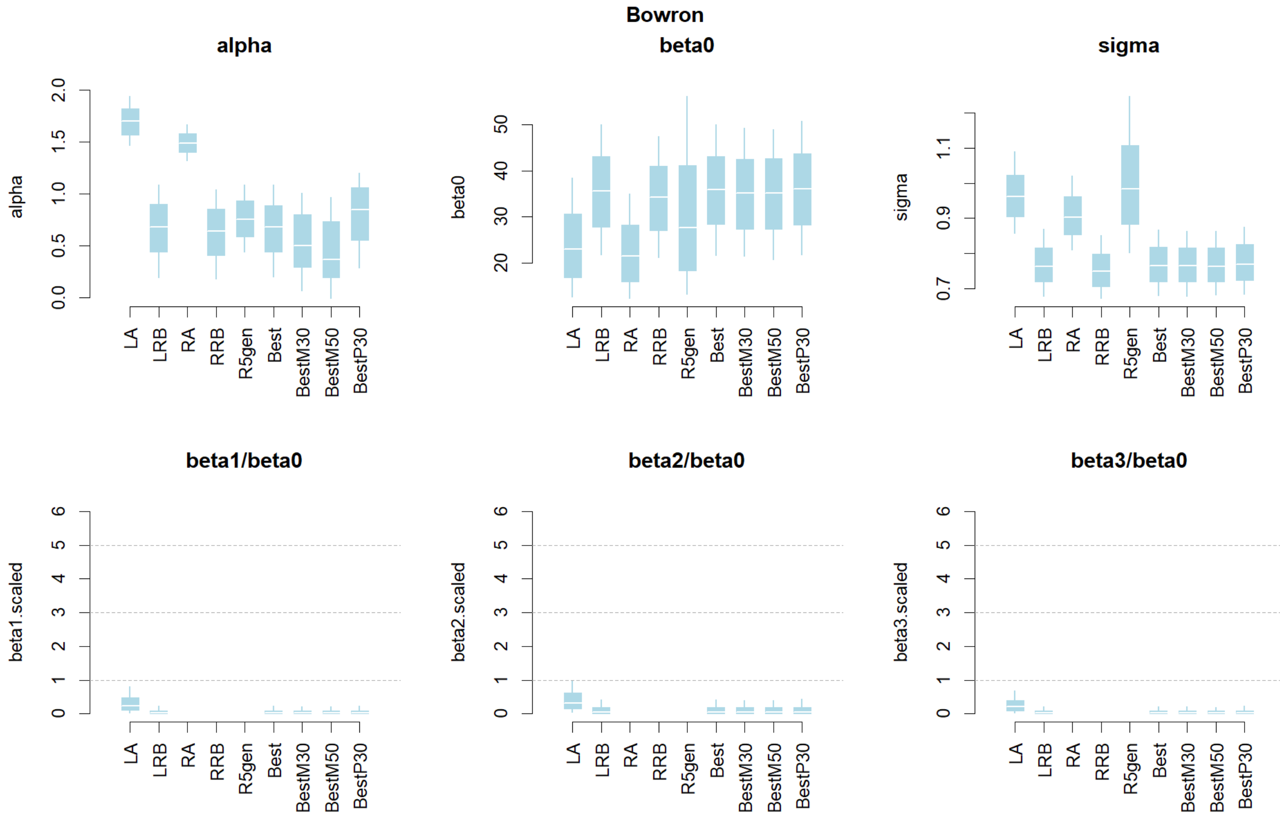

Figure 26. Posterior Distributions for Alternative SR model Parameters – Bowron (DU2) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

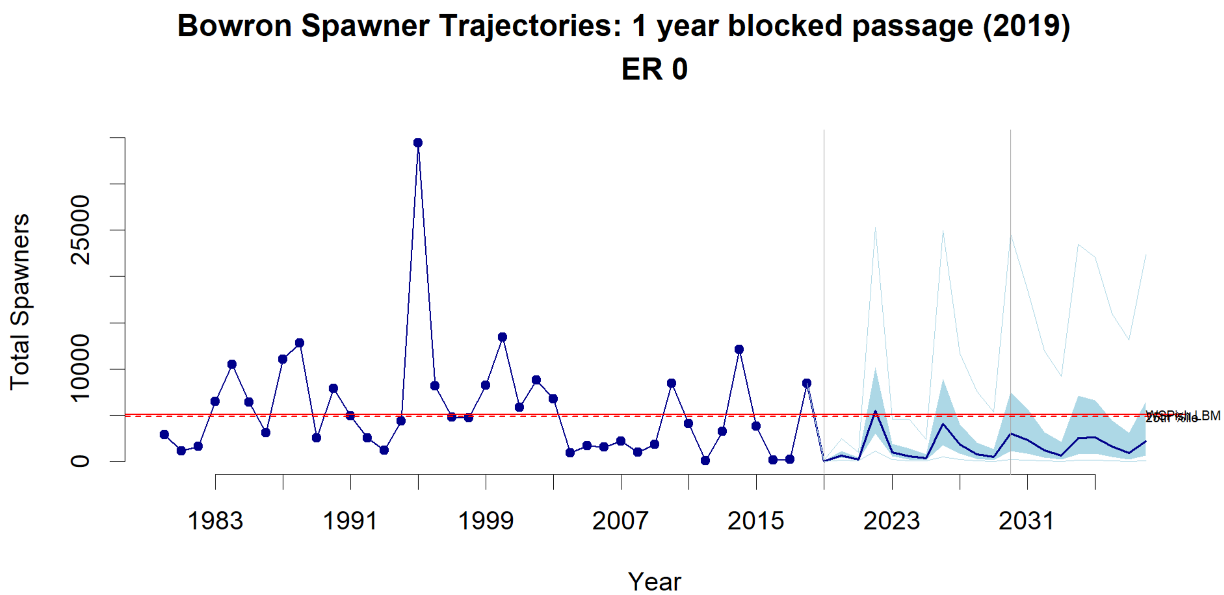

Figure 27. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions – Bowron (DU2) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

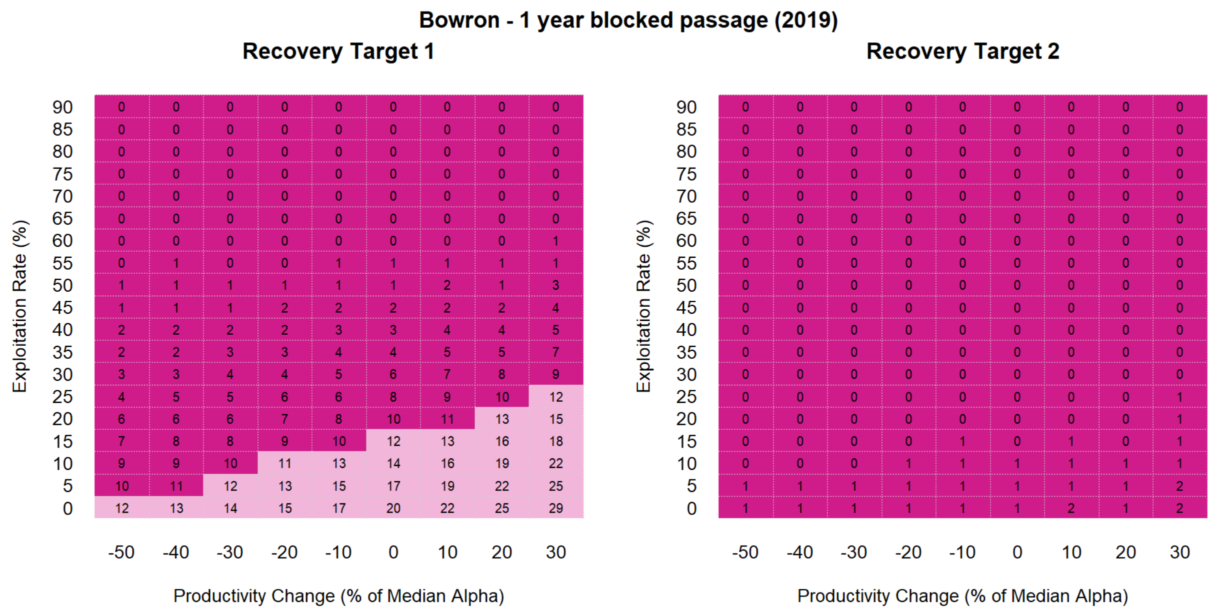

Figure 28. Effect of varying exploitation rate across alternative productivity scenarios – Bowron (DU2) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

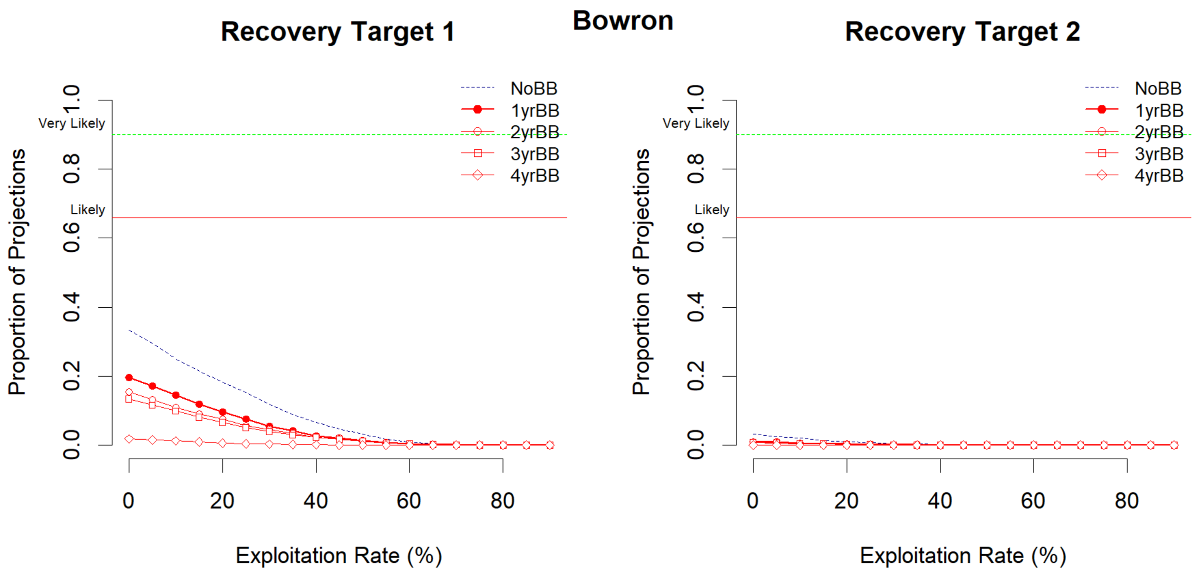

Figure 29. Effect of varying exploitation rate under alternative Big Bar impact scenarios – Bowron (DU2) (Element 20). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate for one of the Big Bar landslide scenarios described in section 6.1.3, where 1yrBB = 99.5% mortality applied to 2019 return year, 2yrBB = 99.5% mortality applied to 2019 and 2020 return years, etc. The thick red line with solid points in this plot corresponds to the "0" productivity change column in the grids shown in the previous plot. The horizontal lines mark the IPCC probability levels for Likely in solid red and Very Likely in dashed green (Table 7).

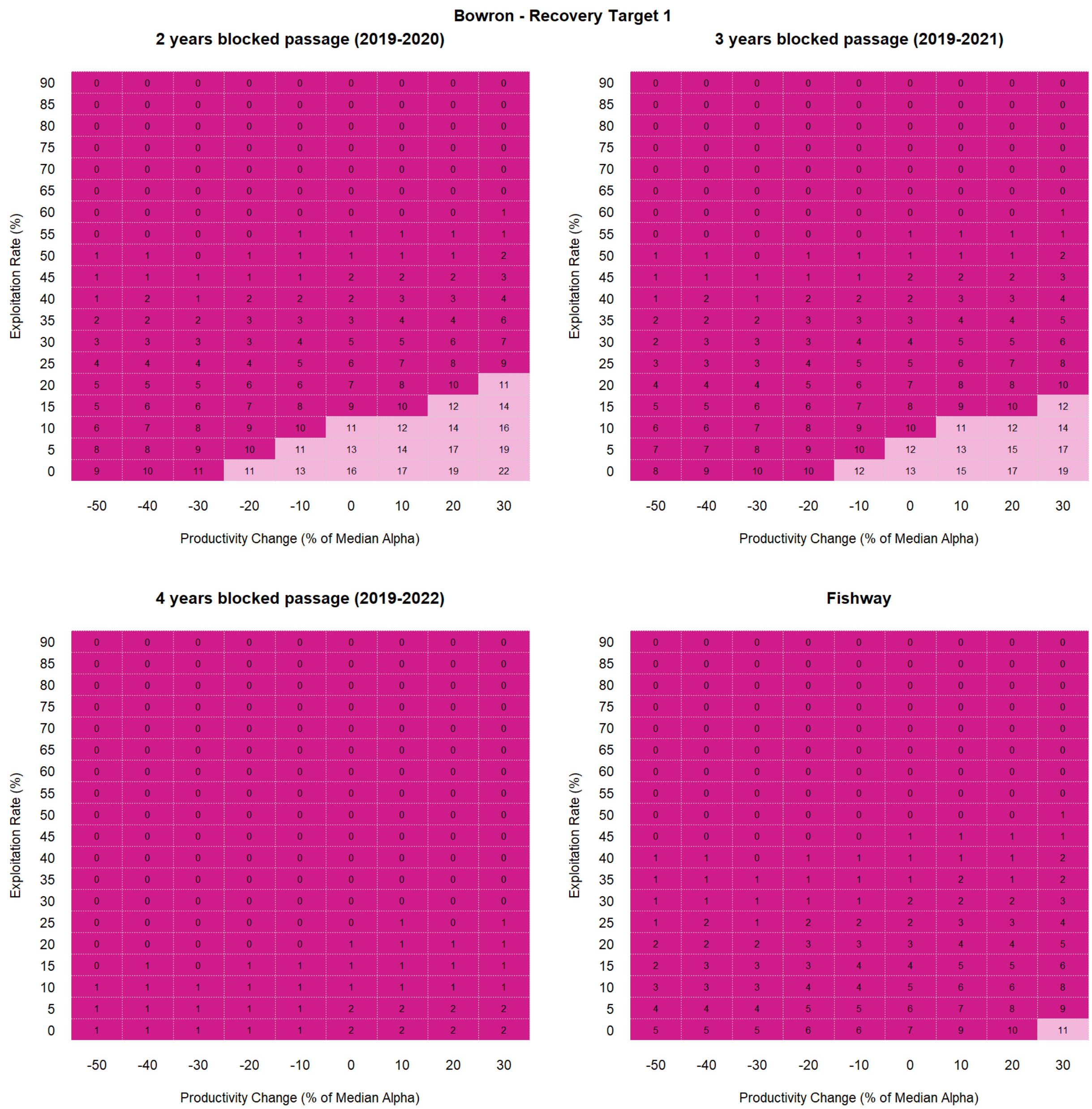

Figure 30. Effect of varying exploitation rate across alternative productivity scenarios in combination with alternative Big Bar impact scenarios – Bowron (DU2) (Element 20). Each panel shows simulated performance relative to Recovery Target #1 (section 5.2) under one of the alternative Big Bar landslide scenarios. Panel layout is the same as the earlier figure. The blocked passage panels each show the effect of 99.5% en-route mortality in the years specified from Big Bar impacts, and the fishway panel scenario was described in section 6.1.3.

13.2.3. Quesnel (Quesnel-S DU16)

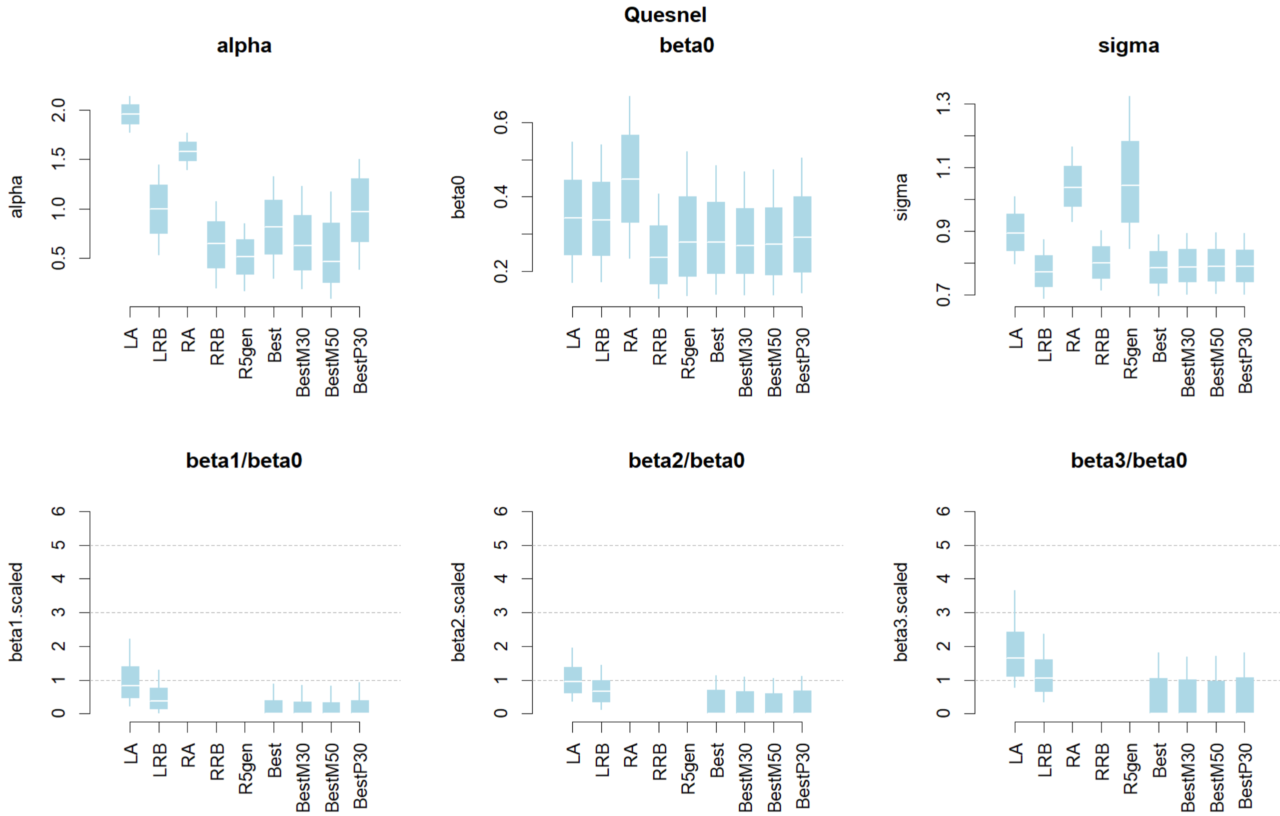

Figure 31. Posterior Distributions for Alternative SR model Parameters – Quesnel (DU16) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

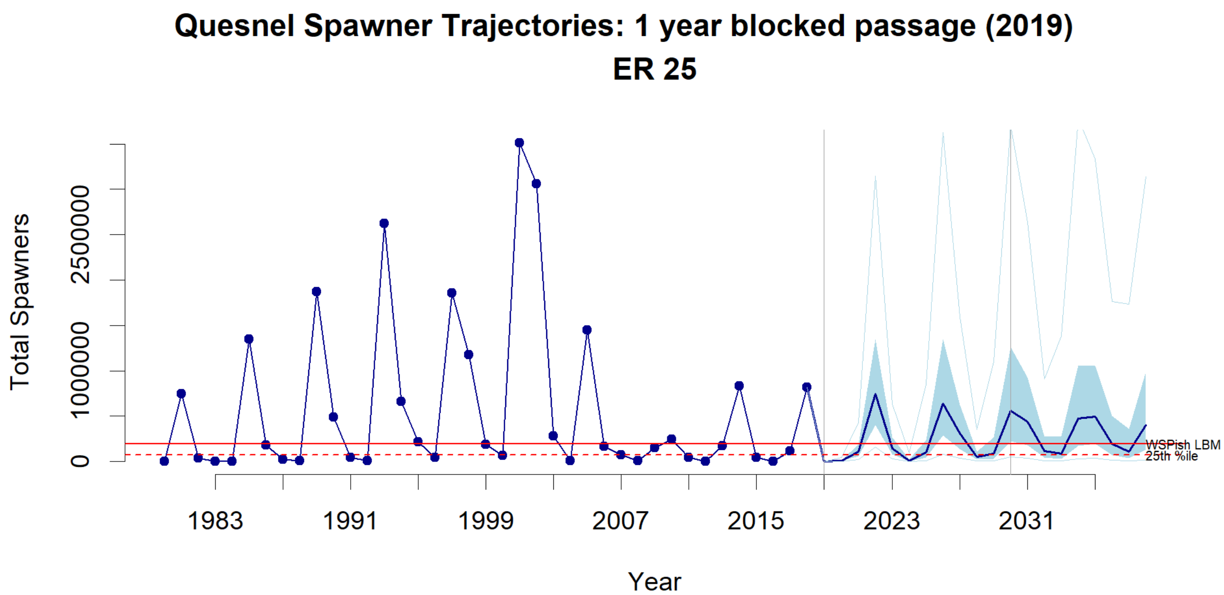

Figure 32. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions – Quesnel (DU16) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

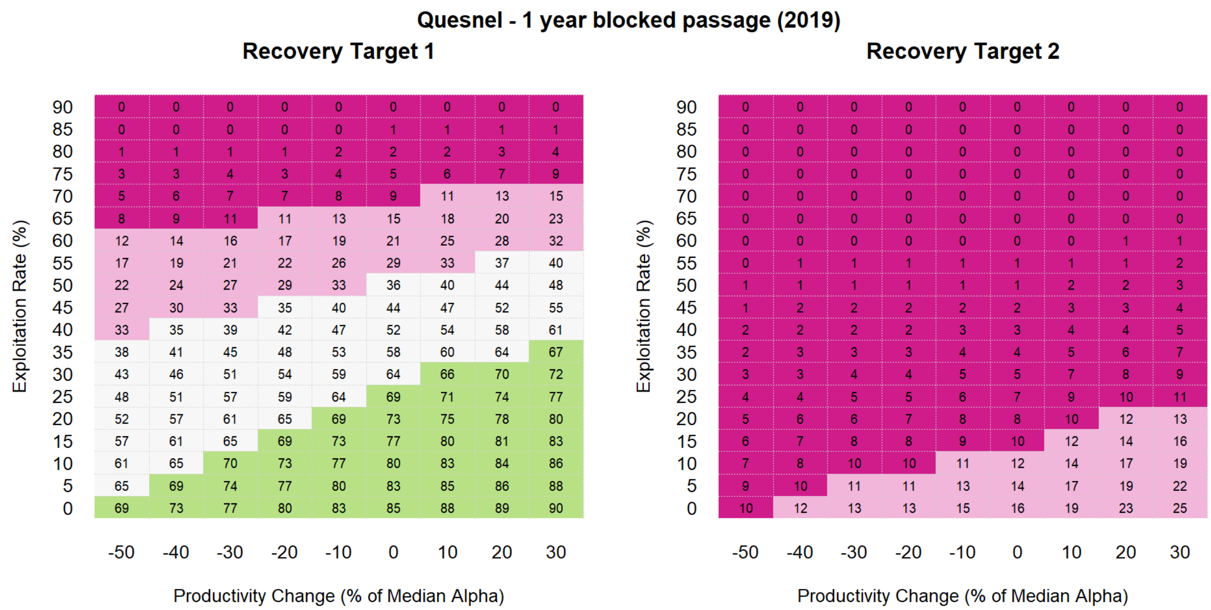

Figure 33. Effect of varying exploitation rate across alternative productivity scenarios – Quesnel (DU16) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

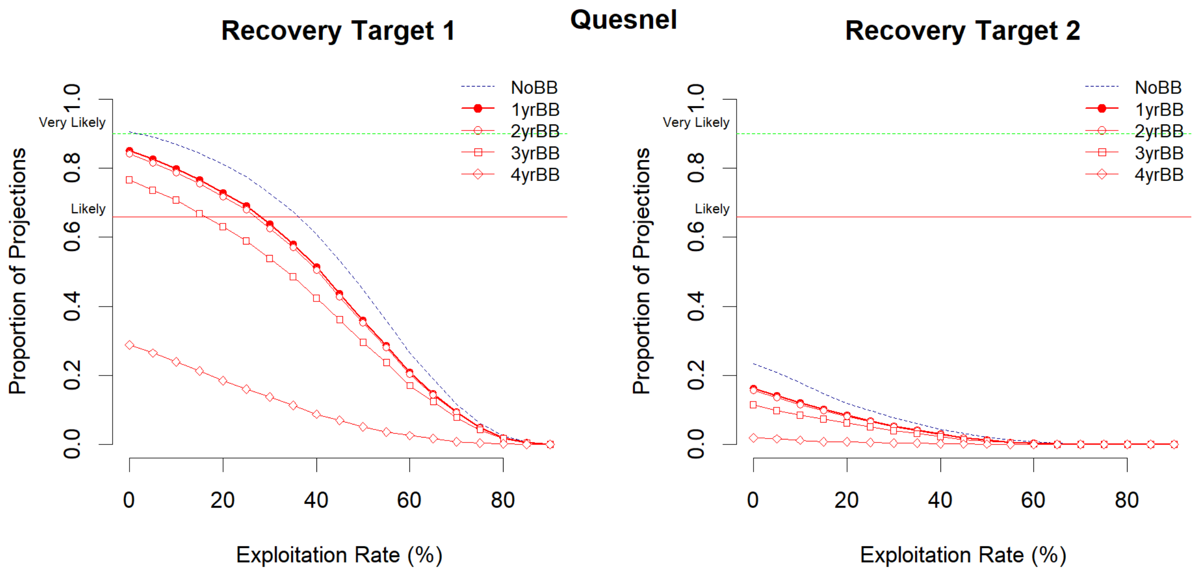

Figure 34. Effect of varying exploitation rate under alternative Big Bar impact scenarios - Quesnel (DU16) (Element 20). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate for one of the Big Bar landslide scenarios described in section 6.1.3, where 1yrBB = 99.5% mortality applied to 2019 return year, 2yrBB = 99.5% mortality applied to 2019 and 2020 return years, etc. The thick red line with solid points in this plot corresponds to the “0” productivity change column in the grids shown in the previous plot. The horizontal lines mark the IPCC probability levels for Likely in solid red and Very Likely in dashed green (Table 7).

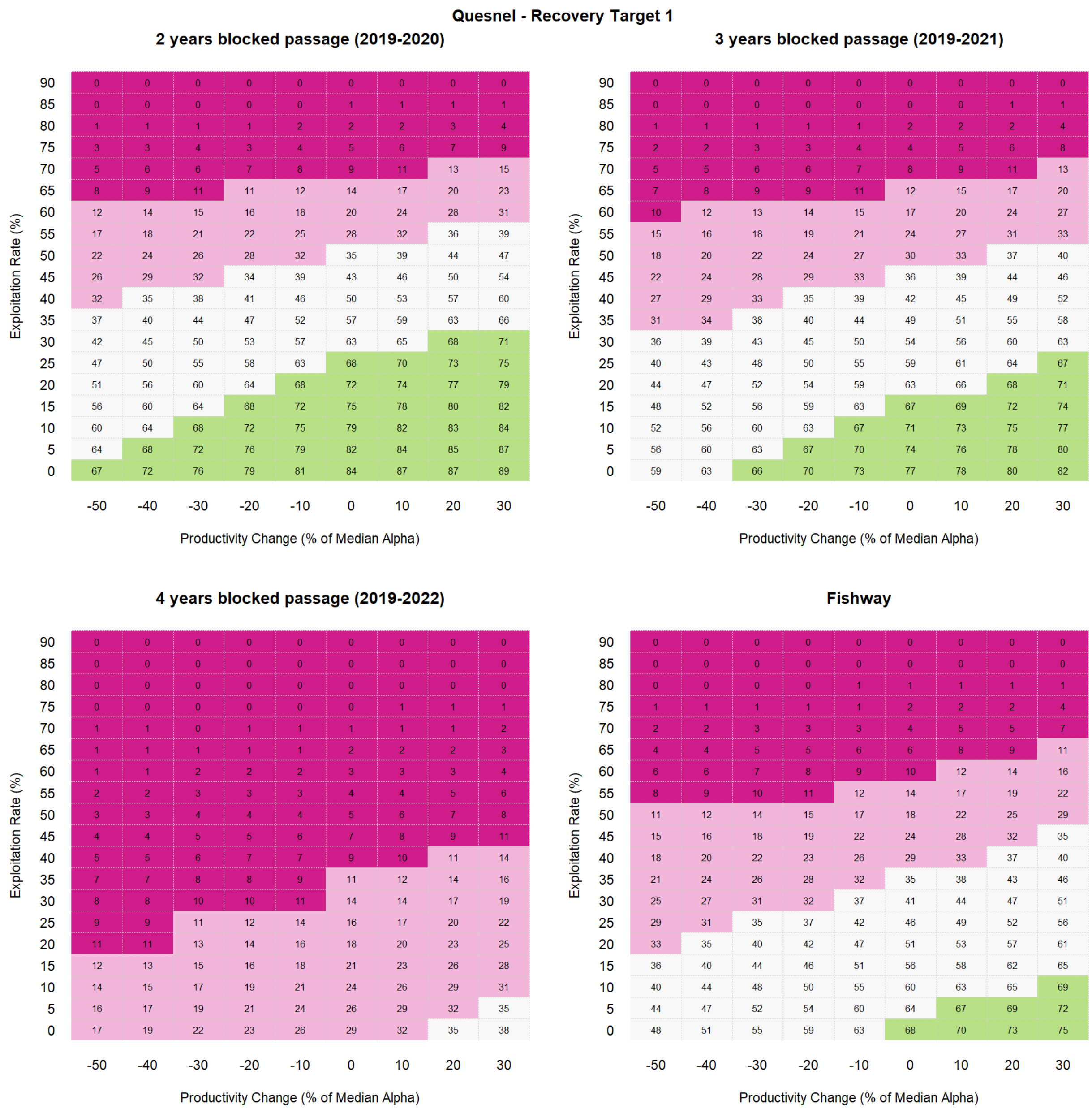

Figure 35. Effect of varying exploitation rate across alternative productivity scenarios in combination with alternative Big Bar impact scenarios – Quesnel (DU16) (Element 20). Each panel shows simulated performance relative to Recovery Target #1 (section 5.2) under one of the alternative Big Bar landslide scenarios. Panel layout is the same as the earlier figure. The blocked passage panels each show the effect of 99.5% en-route mortality in the years specified from Big Bar impacts, and the fishway panel scenario was described in section 6.1.3.

13.2.4. Late Stuart (Takla-Trembleur-Stuart-S DU21)

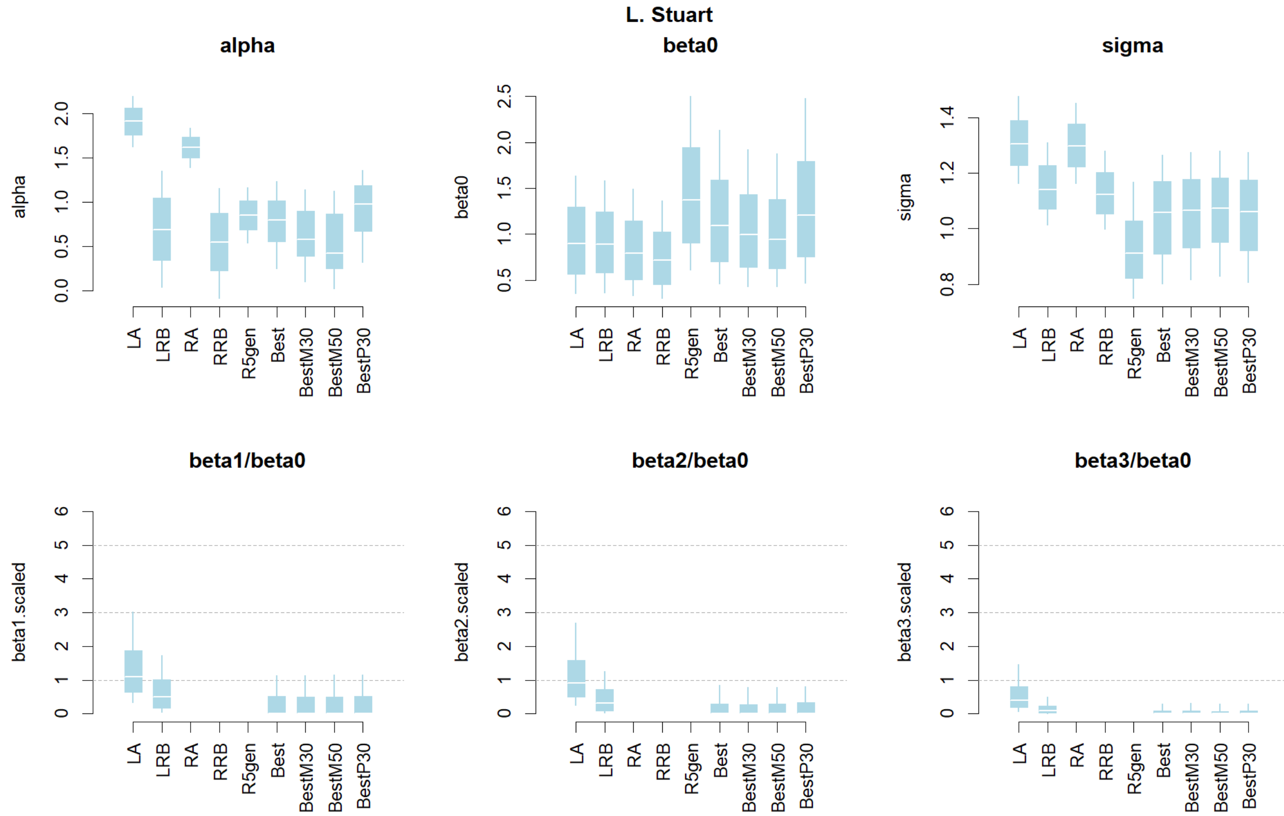

Figure 36. Posterior Distributions for Alternative SR model Parameters - Late Stuart (DU21) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.

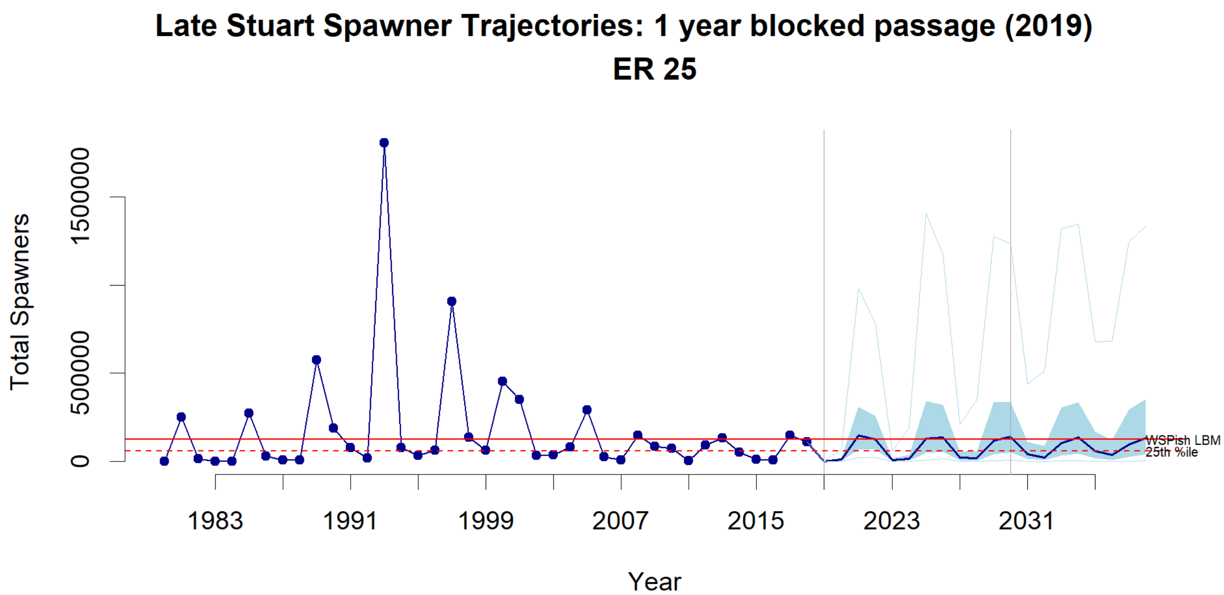

Figure 37. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions - Late Stuart (DU21) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.

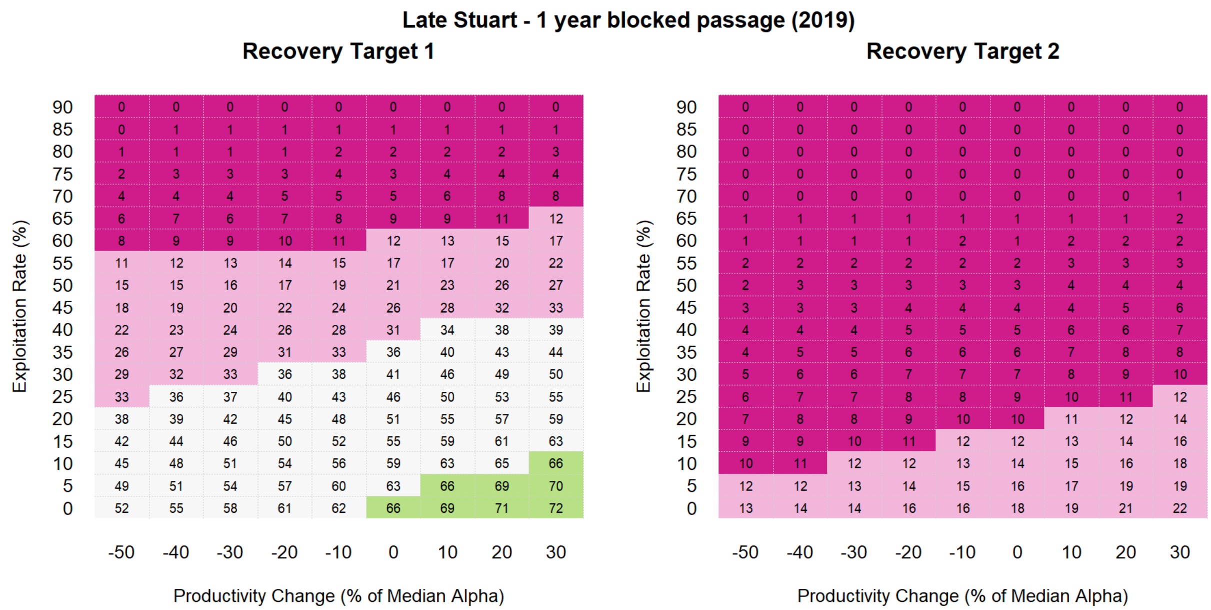

Figure 38. Effect of varying exploitation rate across alternative productivity scenarios - Late Stuart (DU21) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled “0”. Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.

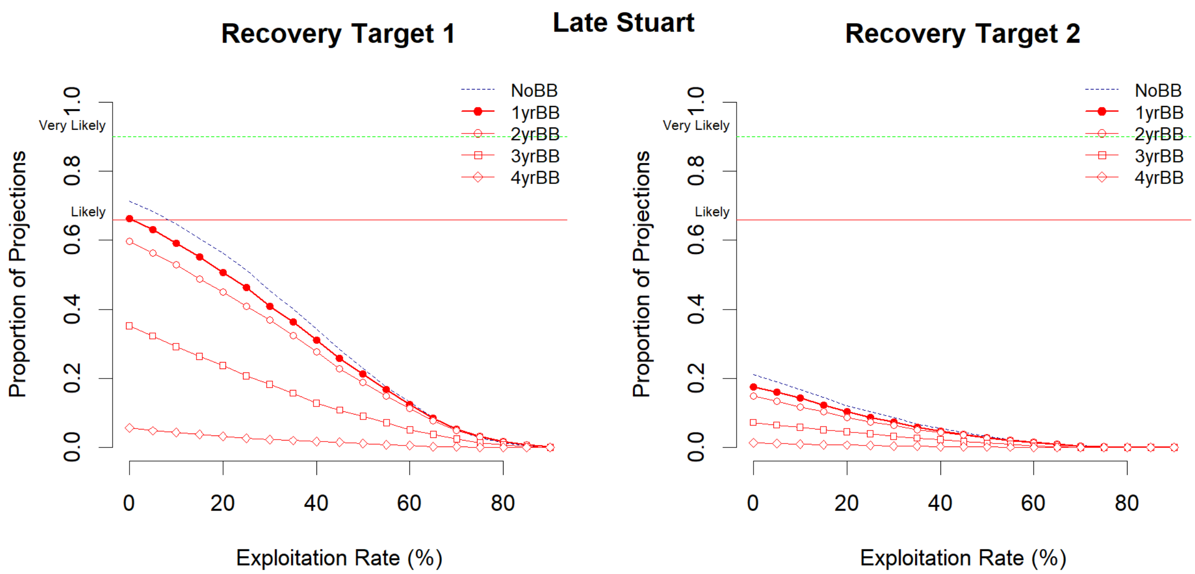

Figure 39. Effect of varying exploitation rate under alternative Big Bar impact scenarios - Late Stuart (DU21) (Element 20). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate for one of the Big Bar landslide scenarios described in section 6.1.3, where 1yrBB = 99.5% mortality applied to 2019 return year, 2yrBB = 99.5% mortality applied to 2019 and 2020 return years, etc. The thick red line with solid points in this plot corresponds to the "0" productivity change column in the grids shown in the previous plot. The horizontal lines mark the IPCC probability levels for Likely in solid red and Very Likely in dashed green (Table 7).

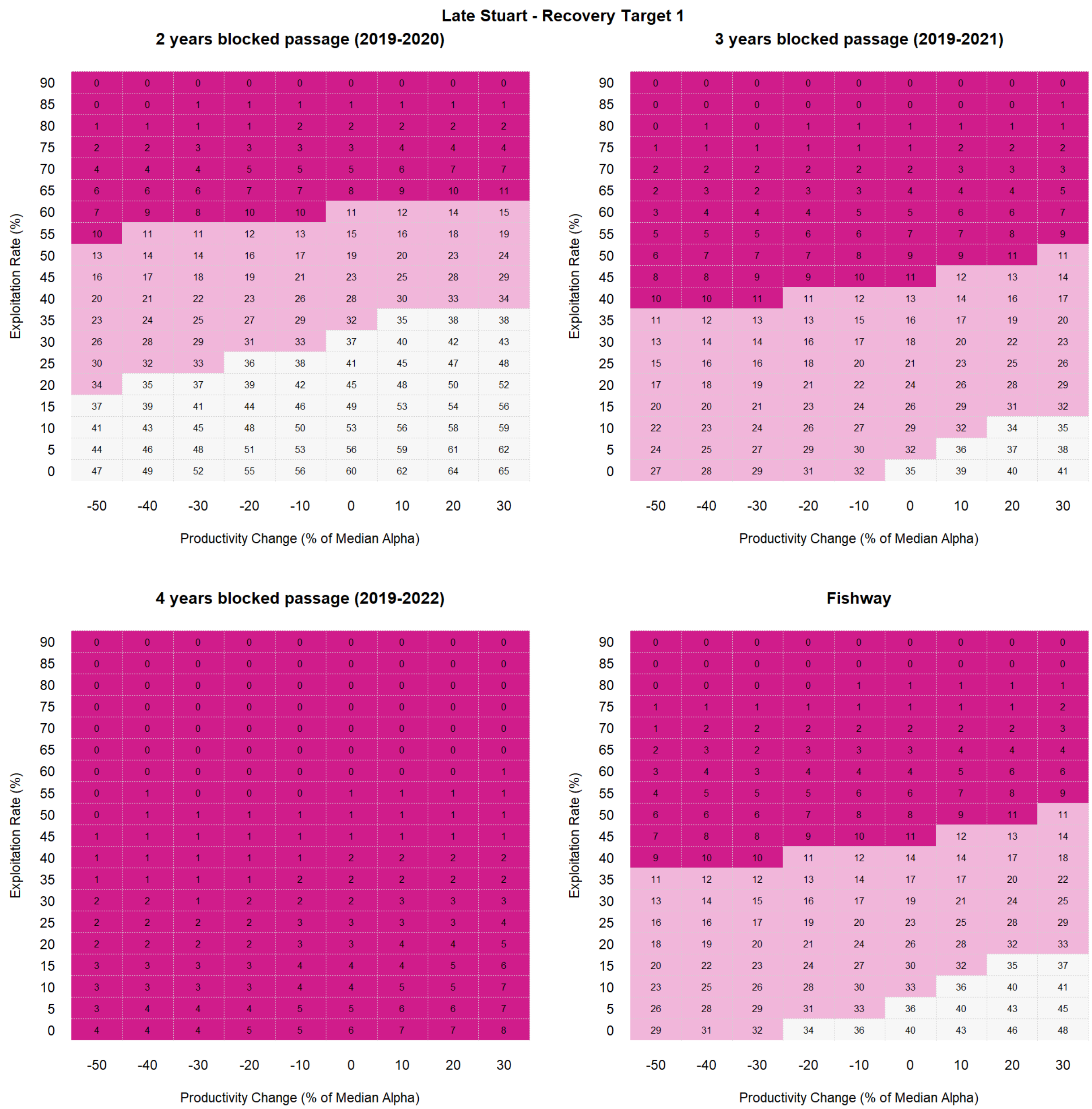

Figure 40. Effect of varying exploitation rate across alternative productivity scenarios in combination with alternative Big Bar impact scenarios - Late Stuart (DU21) (Element 20). Each panel shows simulated performance relative to Recovery Target #1 (section 5.2) under one of the alternative Big Bar landslide scenarios. Panel layout is the same as the earlier figure. The blocked passage panels each show the effect of 99.5% en-route mortality in the years specified from Big Bar impacts, and the fishway panel scenario was described in section 6.1.3.

13.2.5. Taseko (Taseko-ES DU 22)

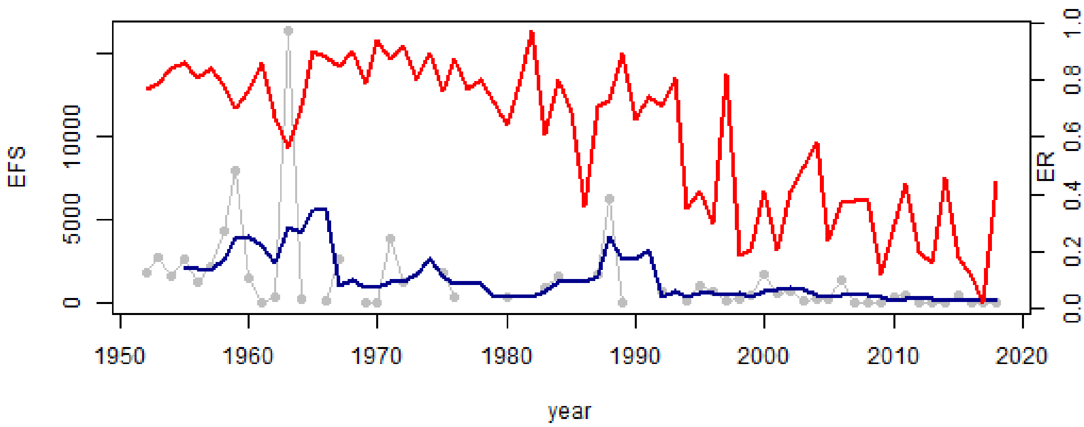

Figure 41. Time Series of Effective Female Spawners (annual in gray, 1 generation running average in blue solid line) and Exploitation Rate (red line) – Taseko (DU22) (Element 2).

13.3. SPECIAL CONCERN

13.3.1. Raft* (Kamloops-ES DU11)

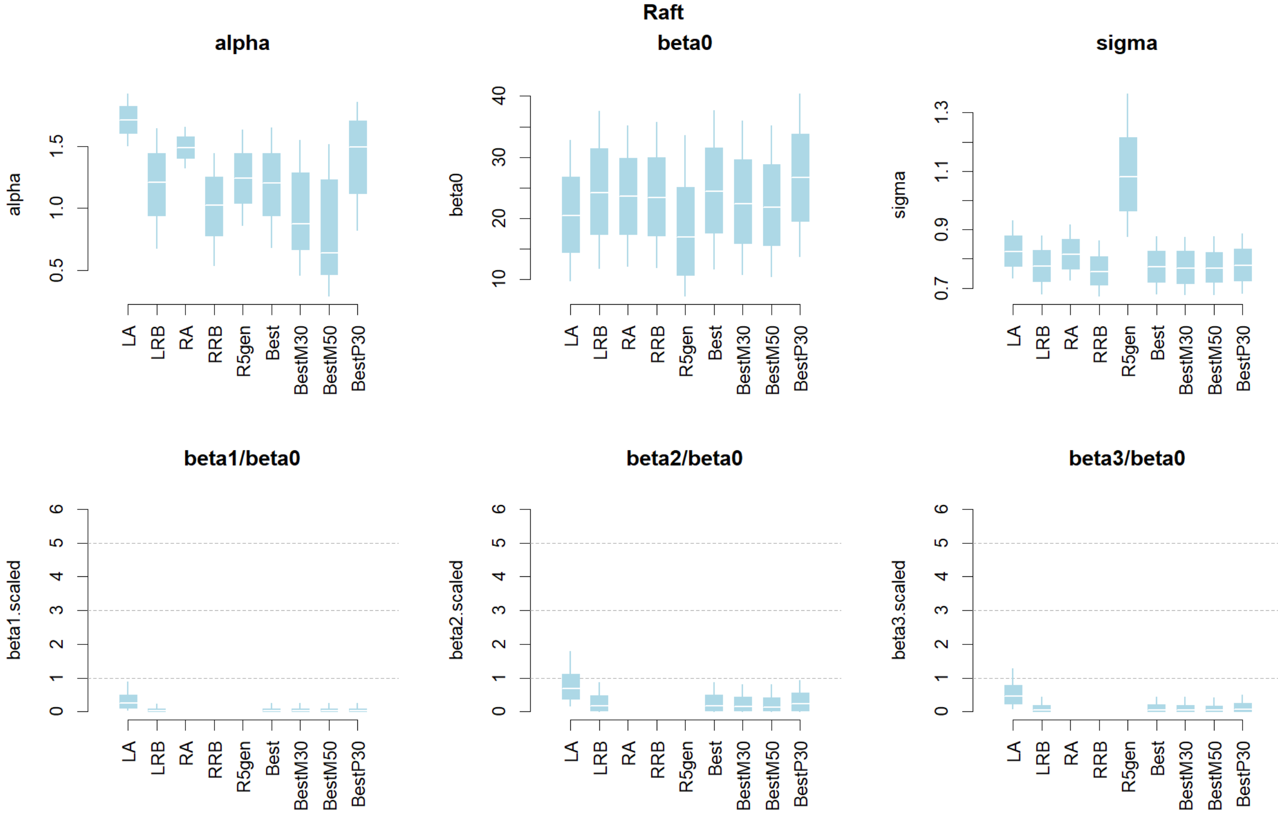

Figure 42. Posterior Distributions for Alternative SR model Parameters – Raft (DU11) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.*

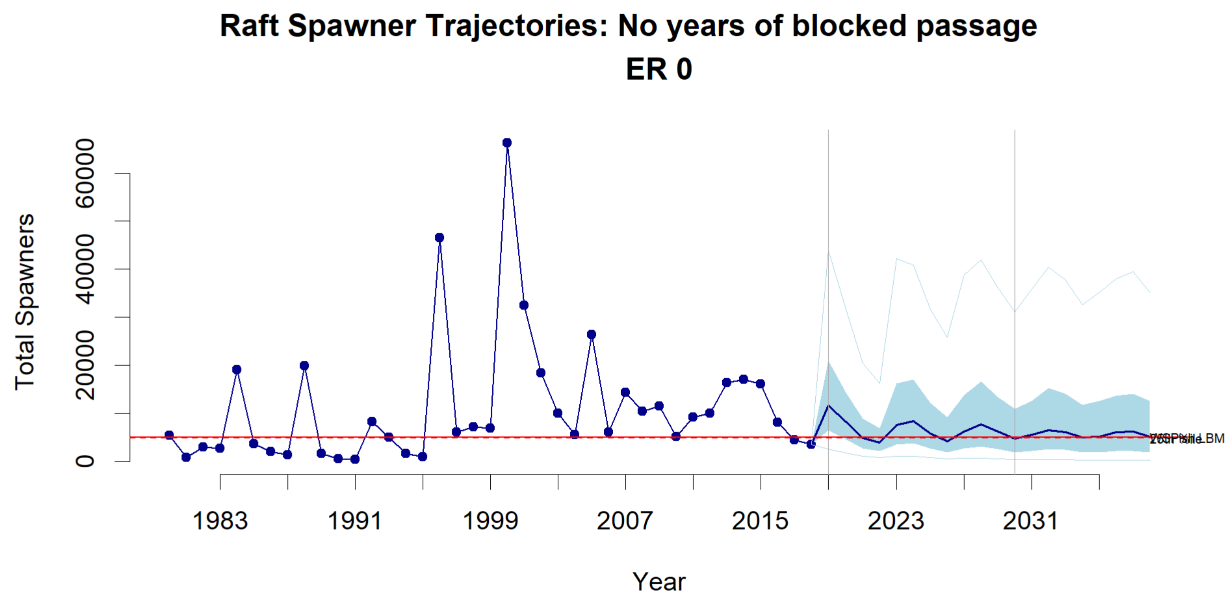

Figure 43. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions – Raft (DU11) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.*

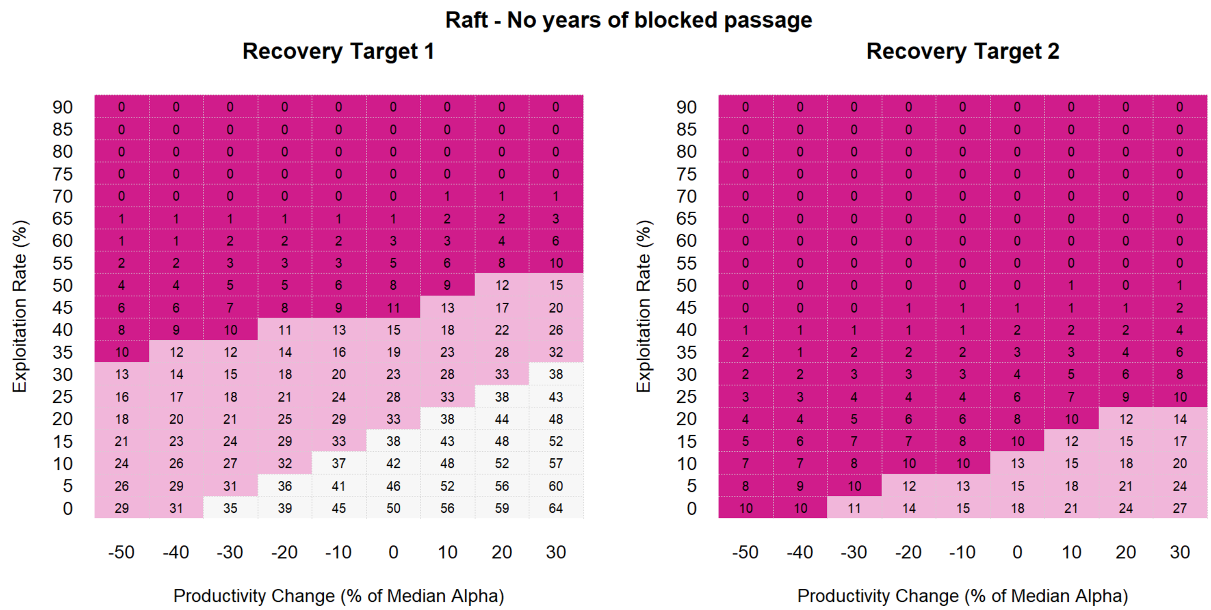

Figure 44. Effect of varying exploitation rate across alternative productivity scenarios - Raft (DU11) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.*

13.3.2. Birkenhead* (Lillooet-Harrison-L DU12)

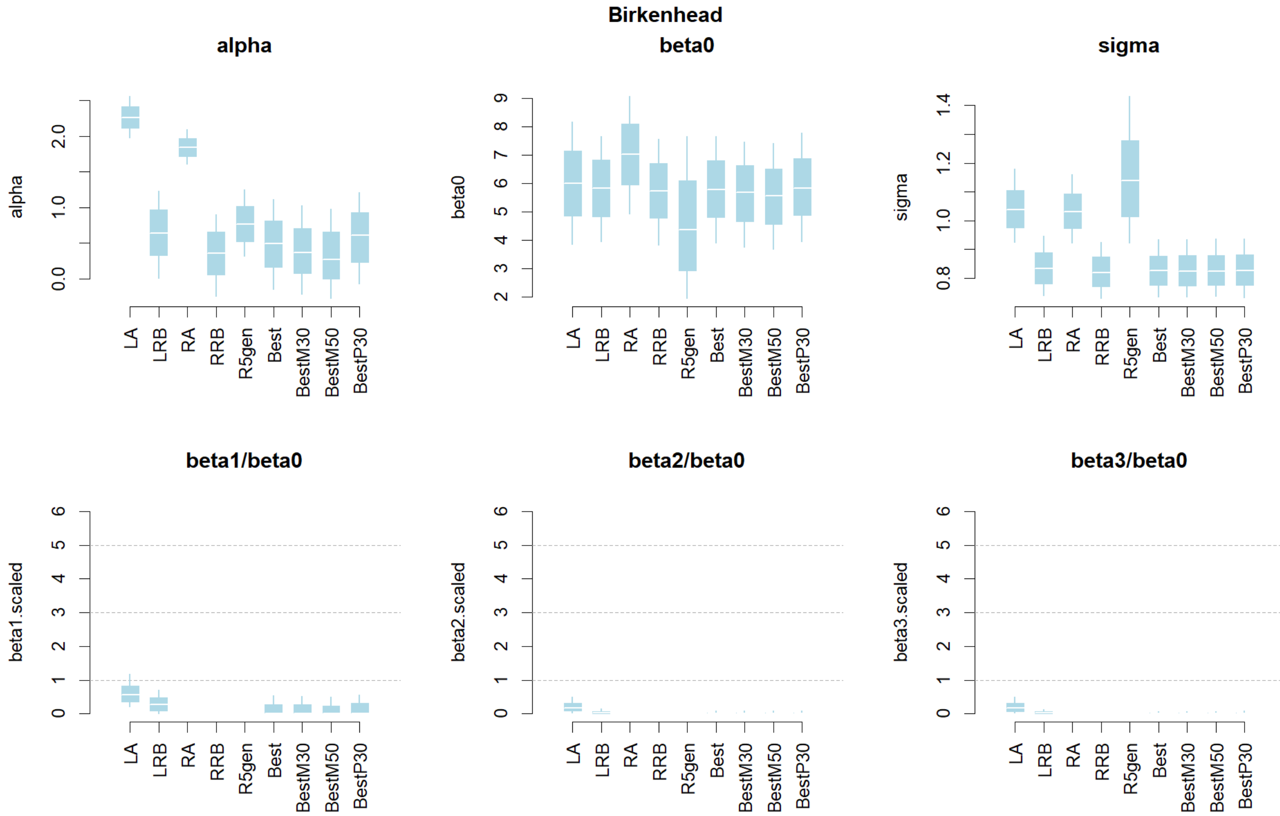

Figure 45. Posterior Distributions for Alternative SR model Parameters – Birkenhead (DU12) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.*

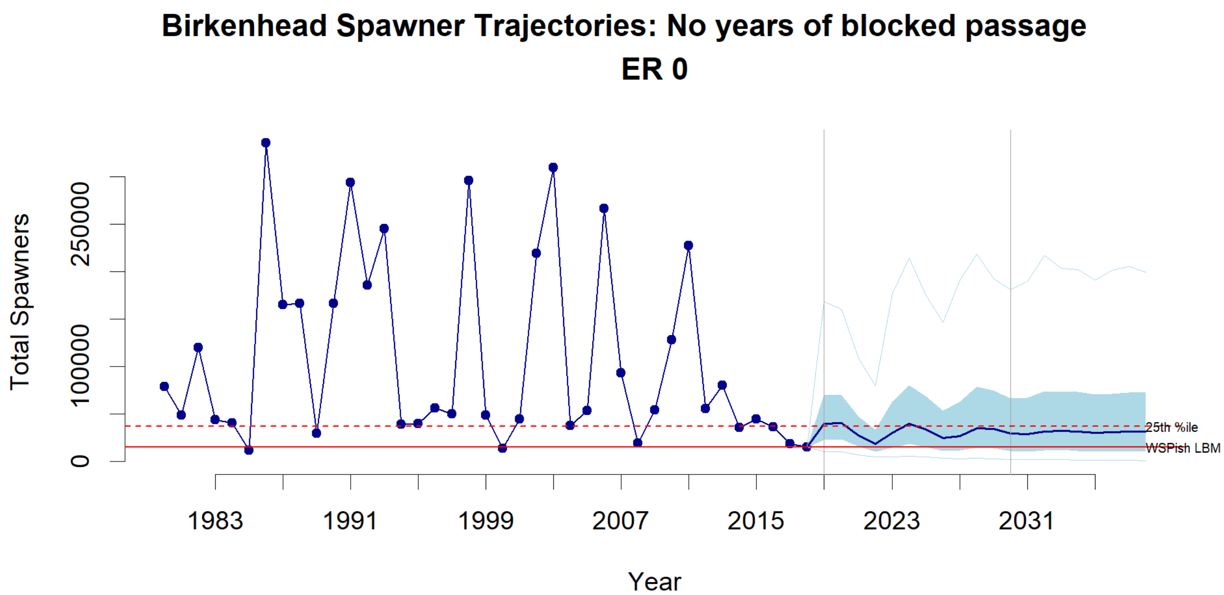

Figure 46. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions – Birkenhead (DU12) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.*

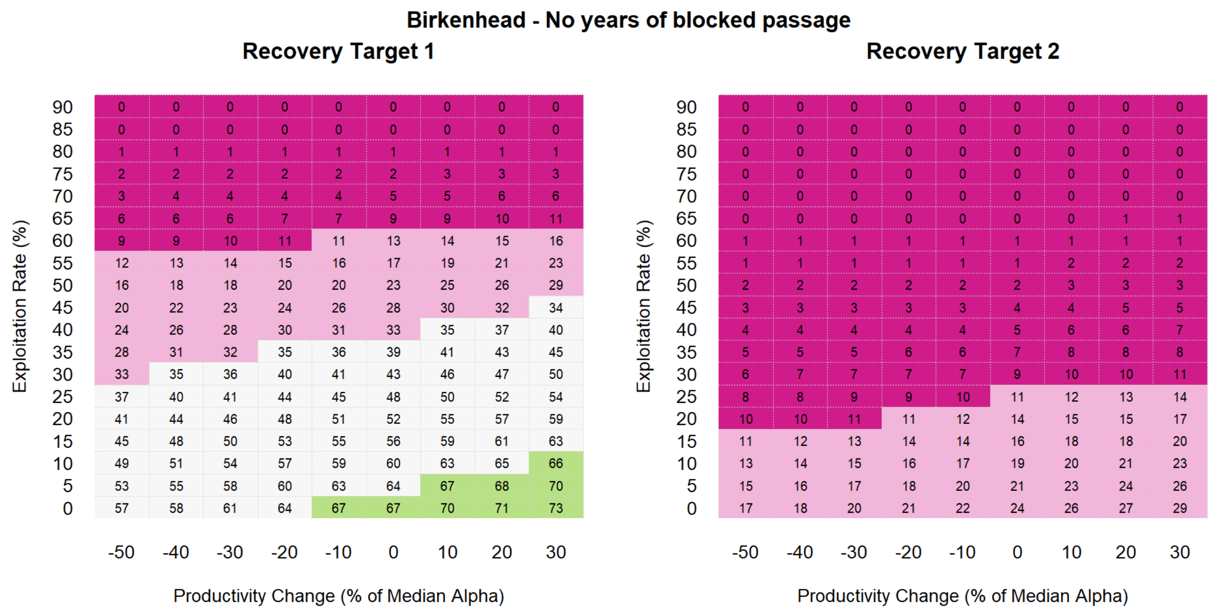

Figure 47. Effect of varying exploitation rate across alternative productivity scenarios - Birkenhead (DU12) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.*

13.3.3. Stellako* (Francois-Fraser-S DU7)

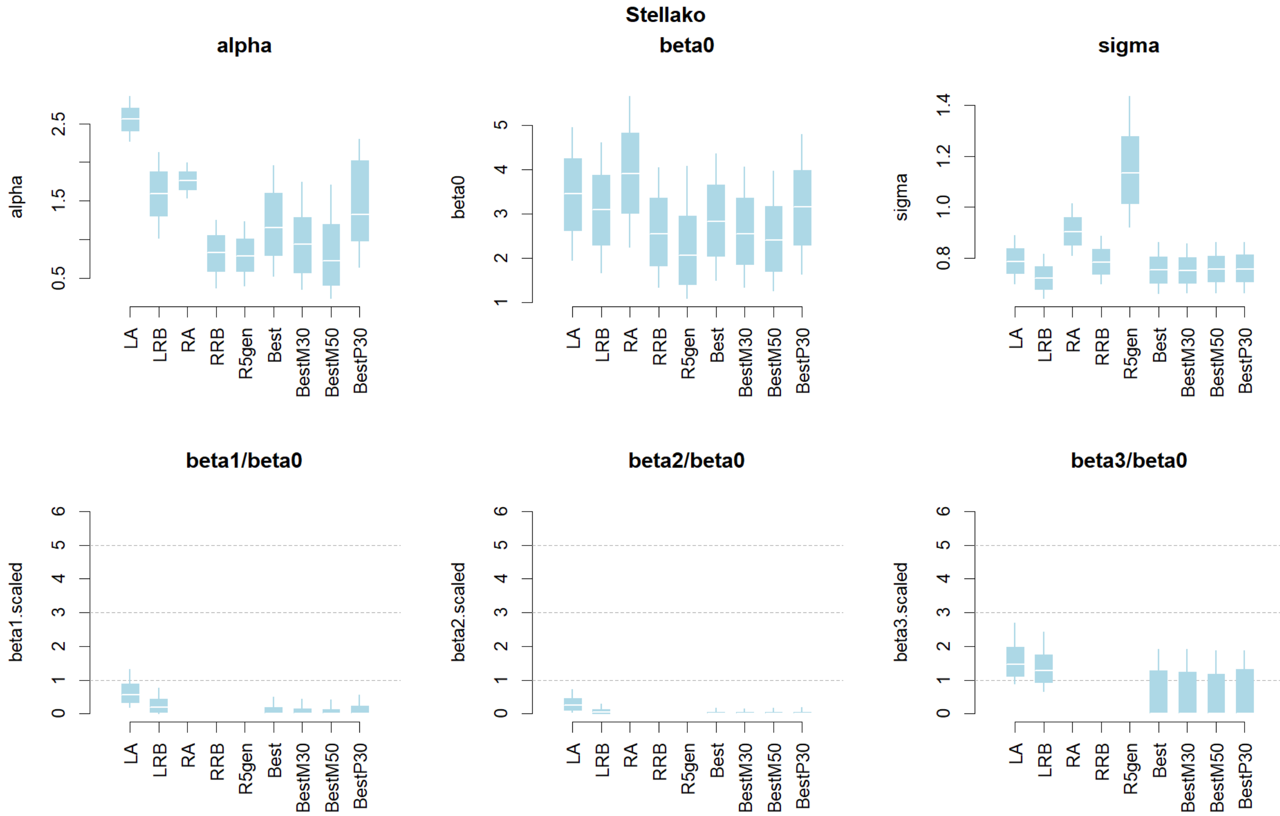

Figure 48. Posterior Distributions for Alternative SR model Parameters – Stellako (DU7) (Element 13 part 1). Each panel shows the posterior distribution for one stock-recruit model parameter across the five alternative models described in section 5.3.2, the stock-specific model(s), and three examples of the stock-specific model(s) with rescaled productivity. LA = Larkin model, LRB = recursive Bayesian Larkin model, RA = Ricker model, RRB = recursive Bayesian Ricker model, R5Gen = Ricker model using last 5 generations of stock-recruit estimates, Best = stock specific model(s) per Table 6 in section 5.3.4, BestM30 = Best with median alpha parameter minus 30%, BestM50 = minus 50%, Best P30 = plus 30%. The bottom row shows the distributions for lag betas, re-scaled relative to β_0.*

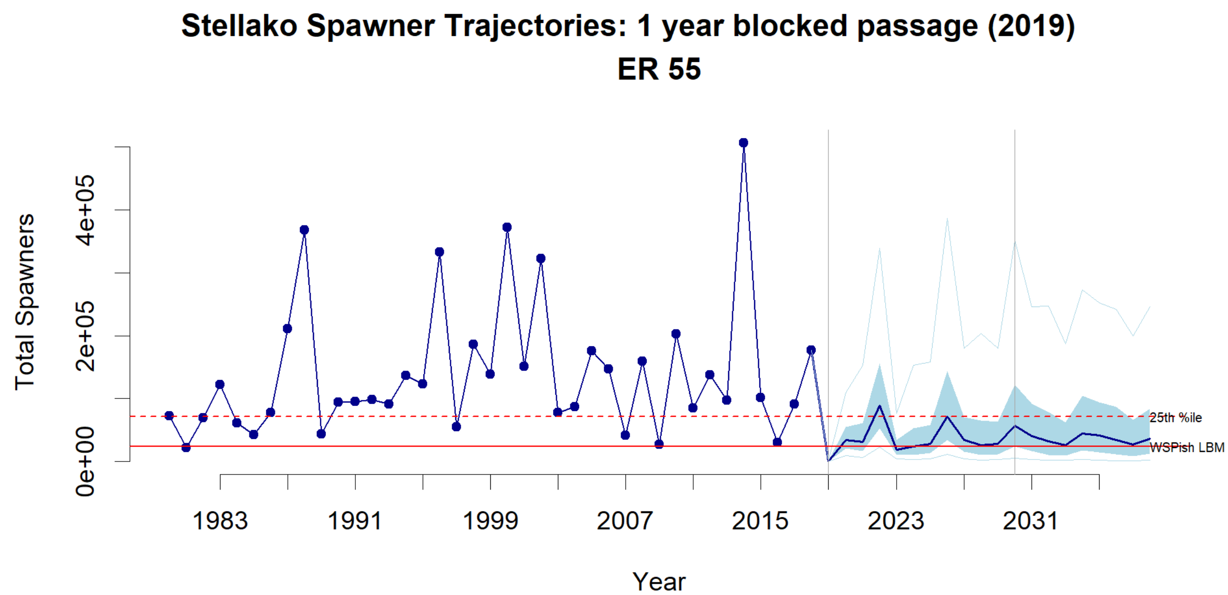

Figure 49. Simulated Trajectory for Max ER Likely to Achieve Not Endangered or Threatened under Base Case assumptions - Stellako (DU7) (Element 15). The line with solid points shows observed spawners from 1980 to 2018. The spread to the right shows the distribution of simulated spawner abundances (solid line = median, blue shaded area = p25-p75, dashed lines = p10 to p90). The horizontal red dashed line marks the 25th percentile of all observed spawner abundances. The vertical grey lines delineate the 3 generation time window used to calculate the performance measures described in Table 5.*

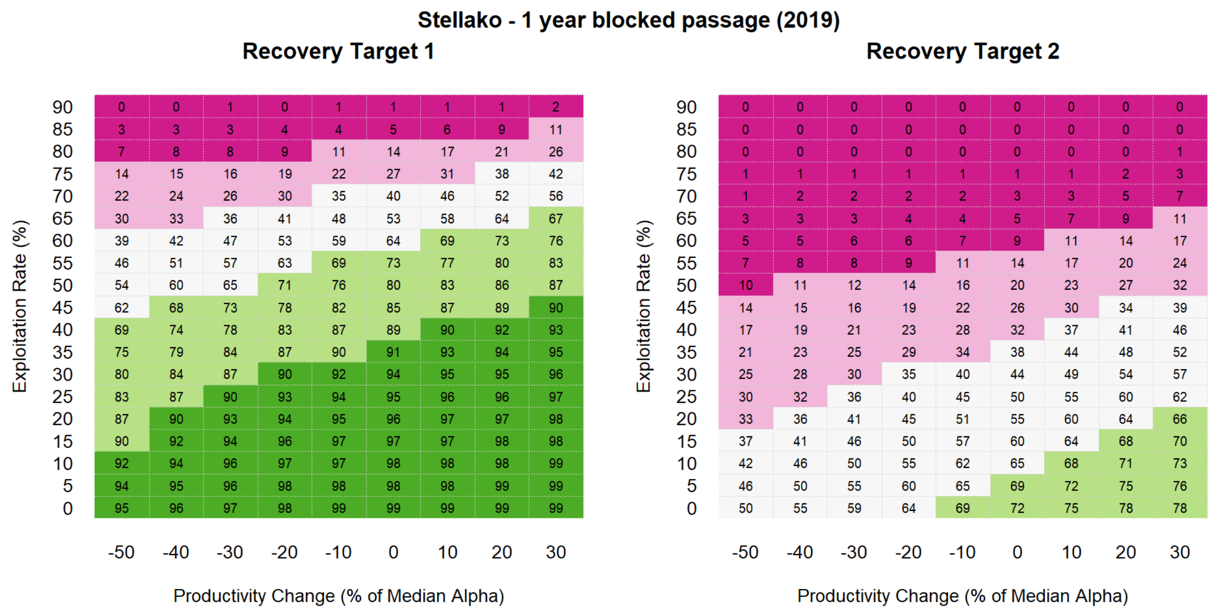

Figure 50. Effect of varying exploitation rate across alternative productivity scenarios - Stellako (DU7) (Element 15). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate (along a column) and changing productivity (along a row). Current productivity is shown in the the Productivity Change column labelled "0". Numbers in each cell are the percentage of simulated trajectories out of 5000 that meet the Recovery Target. Colour coding overlays the IPCC probability levels (Table 7) from Very Likely in dark green to Very Unlikely in dark magenta. For DUs that spawn upstream of the Big Bar landslide, a 99.5% in-river en-route mortality rate was modelled in the 2019 simulation year.*

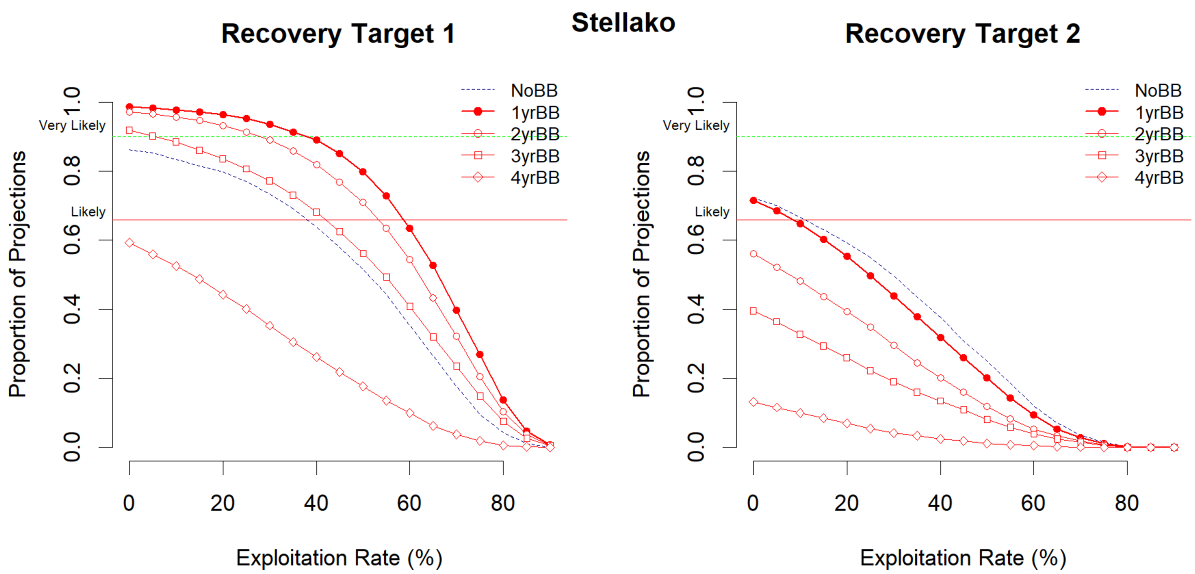

Figure 51. Effect of varying exploitation rate under alternative Big Bar impact scenarios - Stellako (DU7) (Element 20). These two panels show simulated performance relative to Recovery Target #1 and Recovery Target #2 described in section 5.2. Each panel summarizes performance for simulations with changing exploitation rate for one of the Big Bar landslide scenarios described in section 6.1.3, where 1yrBB = 99.5% mortality applied to 2019 return year, 2yrBB = 99.5% mortality applied to 2019 and 2020 return years, etc. The thick red line with solid points in this plot corresponds to the "0" productivity change column in the grids shown in the previous plot. The horizontal lines mark the IPCC probability levels for Likely in solid red and Very Likely in dashed green (Table 7).*

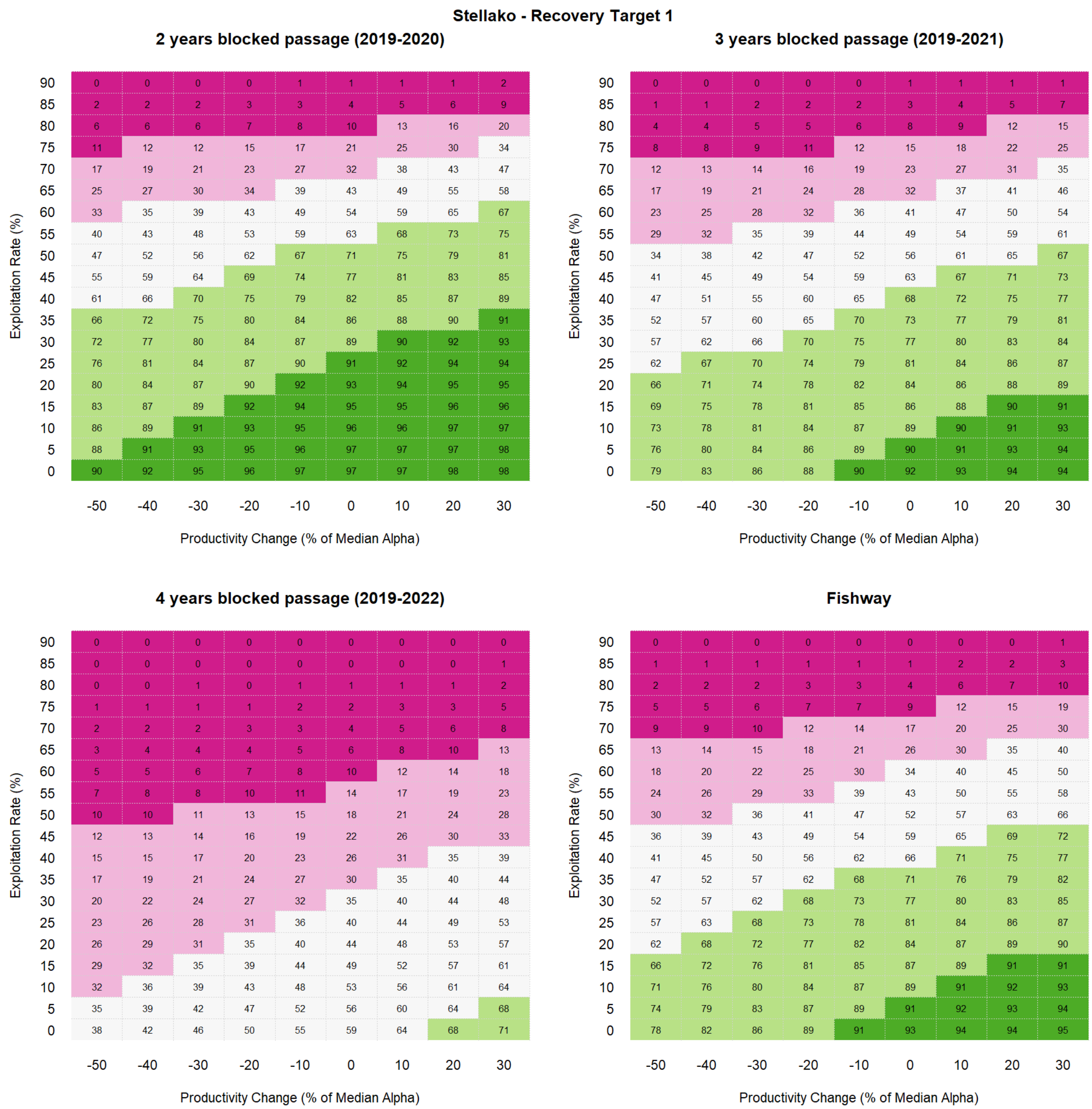

Figure 52. Effect of varying exploitation rate across alternative productivity scenarios in combination with alternative Big Bar impact scenarios - Stellako (DU7) (Element 20). Each panel shows simulated performance relative to Recovery Target #1 (section 5.2) under one of the alternative Big Bar landslide scenarios. Panel layout is the same as the earlier figure. The blocked passage panels each show the effect of 99.5% en-route mortality in the years specified from Big Bar impacts, and the fishway panel scenario was described in section 6.1.3.*

14. APPENDIX 4: CODE

14.1. PARAMETER ESTIMATION: RICKER MODEL (RA)

```
  model{
         for( i in 1 : N) {
          R_Obs[i] ~ dlnorm(R[i],tau_R)
          R[i] <- RS_log[i] + log(S[i])

          # Ricker
          RS_log[i] <-alpha - beta0 * S[i]

          resid[i] <- log(R_Obs[i]) - R[i]
          Rep[i] ~ dlnorm(R[i],tau_R)
         }
          alpha ~ dnorm(0,0.001)
          beta0 <- 1/Smax
          Smax~ dlnorm(log_Shi,1)I(,sShi)
          sShi <- 3*Shi
          log_Shi<- log(Shi)
          Smax0~ dlnorm(log_Shi,1)I(,sShi)
          tau_R ~ dgamma(0.001,0.001)
          sigma <- 1 / sqrt(tau_R)
```

14.2. PARAMETER ESTIMATION: RECURSIVE BAYESIAN RICKER MODEL (RRB)

```
model{
        for (i in 1:N){
          R_Obs[i] ~ dlnorm(Y[i],tau_R)
          Y[i] <- RS[i] +log(S[i])
          RS[i] <- alpha[i] - beta0 * S[i]
          year[i]<-i
          Rep[i] ~ dlnorm(Y[i],tau_R)
          }
          for (i in 2:N){
          alpha[i] <- alpha[i-1] + w[i]
          w[i]~ dnorm(0,tauw)
        }


          alpha[1]~ dnorm(p.alpha,tau_alpha)
          beta0 <- 1/Smax
          Smax~ dlnorm(log_Shi,1)I(,sShi)
          sShi <- 3*Shi
          log_Shi<- log(Shi)

          tau_R~ dgamma(0.01,0.001)
         varR <- 1/tau_R
          sigma <- 1/pow(tau_R,2)

          tauw~ dgamma(0.01,0.001)
          varw<- 1/tauw
         sigw<- 1/sqrt(tauw)
      }
```

14.3. PERFORMANCE MEASURES AND SCALED RANKING CODE

```
retro.pm <- function(resids,obs){
# resids is a vector of residuals
# obs is a corresponding vector of observed values

out.vec <- rep(NA,5)
names(out.vec) <- c("MRE","MAE","MPE","MAPE","RMSE")

num.obs <- sum(!is.na(resids))

out.vec["MRE"] <- mre.fn(resids)
out.vec["MAE"] <- mae.fn(resids)
out.vec["MPE"] <- mpe.fn(resids,obs)
out.vec["MAPE"] <- mape.fn(resids,obs)
out.vec["RMSE"] <- rmse.fn(resids)
return(out.vec)
}


mre.fn <- function(resids){ num.obs <-
                sum(!is.na(resids));round(sum(resids,na.rm=TRUE)/num.obs,4)}
mae.fn <- function(resids){ num.obs <-
              sum(!is.na(resids));round(sum(abs(resids),na.rm=TRUE)/num.obs,4)}
rmse.fn <- function(resids){ num.obs <- sum(!is.na(resids))
                             round(sqrt(sum(resids^2,na.rm=TRUE)/num.obs),4)}
mpe.fn <- function(resids,obs){ num.obs <- sum(!is.na(resids))
                               round(sum(resids/obs,na.rm=TRUE)/num.obs,4)}
mape.fn <- function(resids,obs){ num.obs <- sum(!is.na(resids))
                                 round(sum(abs(resids)/obs,na.rm=TRUE)/num.obs,4)}



scaled.ranks <- function(x){

  # adapted from Michael Folkes Fn at
  # https://github.com/MichaelFolkes/forecastR_package/blob/master/R/Module_rankModels.R

  x <- abs(x)
  rank.perpmunit <- (length(x)-1) /(max(x, na.rm=TRUE)-min(x, na.rm = TRUE))
  scaled.rank <- x*rank.perpmunit - min(x, na.rm = TRUE)*rank.perpmunit + 1

  if(length(unique(x))==1){scaled.rank <- rep(NA,length(x))}

  return(scaled.rank)

}
```

14.4. FORWARD SIMULATION CODE

```
################################
# FUNCTION TO DO A BASIC FOWARD SIMULATION

doForwardSim <- function(sr.dat, sr.pars, stock.info,   # data and parameter
                    er = 0.5, erm = 0.1, age.prop = c(0,0.9,0.1),  # scenario settings
                    start.year = 2017, sim.years = 20,   # arguments for the forward sim
                    rec.error= FALSE , prod.scal="none", cap=NULL, min1fish=TRUE, # arguments
for recruits.cf()
                    age.names = c("age3","age4", "age5") ,
                    random.seed = 12345
                    ){

# function to do a simple forward simulation. See notes at the end of the header!

# sr.dat =  SR data (needs to have StkID, yr, rec3, rec4,rec5,rec,totspn)  NOTE: in 1Mill fish
!
# sr.pars = SR parameters (needs to have StkID, alpha, beta0,beta1, beta2, beta3)
      # -> set beta1-beta3 to 0 for Ricker
# stock.info = names etc for each StkID

# The following inputs can be given as single value
        # OR matrix of dim sim.years  x NumStocks
        # OR array dim sim.years  x NumStocks  x NumParSets
# er = Expl Rate
# erm = En-route mortality rate (use pDBE values for Fraser Sockeye)

# ageprop =   either vector of 3 values (for age 3,4,5)
        # OR matrix of  dim 3 x NumStocks
        # OR matrix of  dim 3 x NumStocks x NumParSets

# start year = first year of the simulation. sr.dat must have records
#               up to the year before start yeaer
# sim.years = number of years to simulate forward.

# arguments for recruits.cf
# rec.error: if TRUE, include random error term
# prod.scal="none" or a value or matrix (see recruits.cf)
# cap=NULL,  cap on recruits  (NULL or a vector)
# min1fish = if TRUE, set minimun recruits to 1/(10^6)

# NOTES
# For now this is set up specifically for age 3-5 fish. This currently loops through
# the sim years and uses array calcs to do all traj for all stocks at once.
# This loop/array combo is fast, so stopped trying to make
# purr::map() or apply() work for this iterative case

set.seed(random.seed)

# ---------------------------------------------------------------------------
# PART 0: SETTING UP

# load the packages
require(reshape2); require(tidyverse)

# subset the sr data to 8 yrs before start year
sr.dat <- sr.dat[sr.dat$yr %in% (start.year-8):(start.year-1),]

# get and check the number of parameter sets
num.mcmc <- unique(table(sr.pars$StkID))
```

```
if(length(num.mcmc) !=1){warning("variable number of MCMC sets. Check SR Par input file"); sto
p()}

# reorg the data into arrays
# turn the sr data into matrix (wide format) rather than flat format
spn.mat <- sr.dat %>% dplyr::select(StkID,yr,spn) %>% tidyr::spread(StkID,spn)  %>%
  tibble::remove_rownames() %>% tibble::column_to_rownames(var="yr")

# add the placeholders for sim values
spn.mat <- rbind(spn.mat,matrix(NA,ncol=dim(spn.mat)[2],nrow=sim.years+5,
                    dimnames=list(start.year:(start.year + sim.years +5 - 1),dimnames(spn.mat)
[[2]])))

# expand the matrix into a cube (yrs x stocks x par sets)
spn.arr <- array(rep(unlist(spn.mat,num.mcmc)), dim = c(dim(spn.mat),num.mcmc) )
dimnames(spn.arr) <- list(paste("Year", dimnames(spn.mat)[[1]]),paste("Stock", names(spn.mat)
),paste("Par.Set",1:num.mcmc))

# create matching arrays for rec, run, er, erm, age.prop
array.template <- spn.arr
array.template[,,] <- NA
rec.arr <- run.arr <-  er.arr <- erm.arr <- array.template
age.prop.arr <- array.template[1:3,,]
cap.mat <-  array.template[1,,]

# index of array rows that are for forward sim (i.e. exluding the part with spn seed values
sim.idx <- as.numeric(gsub("Year ","",dimnames(spn.arr)[[1]])) %in% start.year:(start.year+sim
.years-1)

# populate run array with 0s
# (need 0, because adding estimated rec-at-age in each pass through the loop below)
run.arr[sim.idx,,] <- 0

# create SR par array ----------------------------------------
pars.names <-  names(sr.pars)[-1]
stk.ids <- unique(sr.pars$StkID)
# unique keeps order of first occurrence,
# so should be fine even if mcmc file is not sorted by stk id
sr.par.arr <- array(unlist(t(sr.pars[,-1])), dim = c( length(pars.names),num.mcmc,length(stk.i
ds) ) )
dimnames(sr.par.arr ) <- list(pars.names, paste("Par.Set",1:num.mcmc),paste("Stock", stk.ids )
)
sr.par.arr <- aperm(sr.par.arr,c(1,3,2))

# populate er, erm, cap and age.prop arrays -----------------------------------------
# this handles single val, matrix,and array (as long as matrix and array have proper dim as pe
r above!)
er.arr[sim.idx,,] <- er
erm.arr[sim.idx,,] <- erm
if(!is.null(cap)){ cap.mat[,] <- cap }
if(is.null(cap)){ cap.mat <- NULL}

age.prop.arr[,,] <- age.prop
dimnames(age.prop.arr)[[1]] <- age.names

# ---------------------------------------------------
# PART 1: CALCULATE RECRUITS AND RUN FOR SEED SPN

# loop through the seed years and feed into an array
for(row.index in 4:8){
    rec.arr[row.index,,] <- recruits.cf(esc.arr = spn.arr[(row.index-3):row.index,,],
```

```
                                pars.arr = sr.par.arr , SRmodel="larkin_4",
                            # this is the "type" in terms of par (e.g. can feed in
                            #   Ricker pars formatted the same way)
                             SR.which=NA,  # obsolete arg
                             error=rec.error,   prod.scal=prod.scal,  cap.arr=cap.mat,
                             min1fish=min1fish)
    # calculate run from rec
    # keep overwriting the whole thing, because age class
    # contributions to a return "build" with each iteration
    run.arr <- RecToRun.fn(Rec.tmp = rec.arr,Run.tmp = run.arr,
                          Age.Prop = age.prop.arr, brd.yr=row.index)
    } # end looping through seed years

# ---------------------------------------------------
# PART 2: DO THE ANNUAL CALCULATION: Spn -> Rec -> Run

#print("starting sim years --------------------------------")

for(row.index in 9:(dim(spn.arr)[1]-5)){

  # calculate spawners after expl rate and en-route mortality
 spn.arr[row.index,,] <- run.arr[row.index,,] * (1 - er.arr[row.index,,]) * (1-erm.arr[row.ind
ex,,])

 # calculate recruits (notes as above)
 rec.arr[row.index,,] <- recruits.cf(esc.arr = spn.arr[(row.index-3):row.index,,],
                              pars.arr = sr.par.arr ,
                               SRmodel="larkin_4", SR.which=NA, error=rec.error,
                               prod.scal=prod.scal, cap.arr=cap.mat,  min1fish=min1fish)

 # calculate ret from rec (again: keep adding to the run 3,4,5 yrs
 # into the future from each BY)
 run.arr <- RecToRun.fn(Rec.tmp = rec.arr,Run.tmp = run.arr,
                   Age.Prop = age.prop.arr, brd.yr=row.index)
 } # end looping through the sim years

 # remove the 5 incomplete sim years at the end
 yrs.keep <-  paste("Year",(start.year-8):(start.year + sim.years - 1))


return(list(Settings = list(label="Text",rec.error = rec.error),
            Spn = spn.arr[yrs.keep,,], Rec = rec.arr[yrs.keep,,],
            Run = run.arr[yrs.keep,,], ER = er.arr[yrs.keep,,],
            ERM = erm.arr[yrs.keep,,]))

} # end doForwardSim()
```

14.5. RECRUITMENT CALCULATION CODE

From Pestal et al. (2012).

```
recruits.cf<-function(esc.arr,pars.arr, SRmodel="larkin_4",
                      SR.which= "totspn", error=TRUE,
                      prod.scal="none",cap.arr=NULL,min1fish=TRUE){

# calculates total recruits for a brood year based on a 4-yr sequence of escapements
# esc.arr is a subset of Esc.Array -> 4yrs by 19 stocks by 500 parameter sets
# pars.arr is the full Lark.Pars
# prodscal.vec are the productivity scalars the current brood year  - one for each stock
# if prodscal.type = "Total" then it directly scales the total
#               recruits (changing patterns in alpha or betas should be built in)

# NOTE: IN THE RPA MODEL, ALPHA SCALING HAPPENS OUTSIDE OF THIS FUNCTION
#       THROUGH SUBSAMPLING THE MCMC

if(SRmodel=="larkin_4"| SRmodel=="larkin_best" | SRmodel=="ricker" ){
# error = rnorm(mean=0, sd=1)* sigma
# RSpred = alpha - beta0 *esc_0 - beta1 * esc_-1  - beta2 * esc_-2  - beta3 * esc_-3
# Rec = esc * exp(RSpred) * exp (error)

rec.arr <- esc.arr[4,,] * exp( pars.arr["alpha",,] -  pars.arr["beta0",,] * esc.arr[4,,] - par
s.arr["beta1",,] * esc.arr[3,,]  - pars.arr["beta2",,] * esc.arr[2,,] -  pars.arr["beta3",,] *
esc.arr[1,,])

if(error){

#err.tmp<-exp(rnorm(dim(pars.arr)[2] *dim(pars.arr)[3] ,mean = 0, sd = 1)  *  (pars.arr["sigma
",,]^2)/2      )
err.tmp<-exp(rnorm(dim(pars.arr)[2] *dim(pars.arr)[3] ,mean = 0, sd = 1)  *  pars.arr["sigma",
,]     )

rec.arr <- rec.arr * err.tmp


  } # end error




# putting in cap to avoid very large rec
if(!is.null(cap.arr)){

cap.idx <- rec.arr > cap.arr
    rec.arr[cap.idx]  <- cap.arr[cap.idx]

}

 if(min1fish){
    # flag and replace anything with rec for a stock less than 1 fish
        tiny.idx <- rec.arr < 0.000001
        rec.arr[tiny.idx] <- 0.000001
 }



} # end Larkin-type SR
```

```
# PRODUCTIVITY SCALAR
if (!is.null(dim(prod.scal))) { rec.arr <-  rec.arr  * prod.scal}  # end prod.scal


return(rec.arr)


} # end  recruits.cf
```